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Land systems, soils and vegetation of the southern Goldfields and Great Western Woodlands of Western Australia - Volume 1

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No. 99 Volume 1

PA Waddell and PD Galloway

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Acknowledgement of Country

The Department of Primary Industries and Regional Development (DPIRD) acknowledges the Traditional Custodians of Country, the Aboriginal peoples of the many lands that we work on and their language groups throughout Western Australia and recognises their continuing connection to the land and waters. DPIRD respects the continuing culture of Aboriginal peoples and the contribution they make to the life of our regions, and we pay our respects to Elders past, present and emerging.

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Cover: *Eucalyptus salmonophloia* (salmon gum) woodland over an understorey of *Maireana sedifolia* (pearl bluebush) and *Atriplex vesicaria* (bladder saltbush) (photo: PA Waddell)

The authors

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Definition

The southern Goldfields region, as featured in this bulletin, includes areas covered by the following 1:250,000 map sheets: Balladonia, Bencubbin, Boorabbin, Cundeelee, Hyden, Jackson, Kalgoorlie, Kurnalpi, Lake Johnston, Norseman, Southern Cross, Widgiemooltha and Zanthus.

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All photographs are of the southern Goldfields region. Photographs were taken by the authors during field work. Aerial photography was provided by the Western Australian Land Information Authority trading as Landgate.

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Shortened forms

Short form	Long form
AFO	Albany-Fraser Orogen
ASC	Australian Soil Classification
ASL	above sea level
BIF	banded iron formation
cm	centimetre
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DPIRD	Department of Primary Industries and Regional Development
DVG	desert varnish gibber
EC; EC_e	electrical conductivity; electrical conductivity of the saturation extract
EGST	Eastern Goldfields Superterrane
EPS	extracellular polymeric substances
GIS	geographic information system
GPS	global positioning system
IBRA	Interim Biogeographic Regionalisation for Australia
KD	key decreaser
KI	key increaser
km; km^2	kilometre; square kilometre
m; mm	metre; millimetre
Ma	mega annum (a period of 1 million years)
mS/m	millisiemens per metre
PFC	projected foliar cover
PMH	preferred microbial habitat
sp.; spp.; subsp.	species (singular); species (multiple); subspecies
TTG	tonalite-trondhjemite-granodiorite
var.	variety
WA	Western Australia

Summary

Scope of the survey

This bulletin defines and maps the land resources of the southern Goldfields region. It combines and augments previous studies that mapped vegetation, physiography and soil distribution in a hierarchical framework that adheres to state and national standards. Maps and descriptions generated over the course of this survey integrate with similar maps of other areas to seamlessly describe most managed land of Western Australia (WA).

The southern Goldfields region, as featured in this bulletin, includes areas covered by the following 1:250,000 map sheets: Balladonia, Bencubbin, Boorabbin, Cundeelee, Hyden, Jackson, Kalgoorlie, Kurnalpi, Lake Johnston, Norseman, Southern Cross, Widgiemooltha and Zanthus. The area surveyed by field work from 2008 to 2017 covers about 151,753 km^2.

The southern Goldfields survey area is closely aligned with the world's largest and most intact area of Mediterranean-climate woodland, known as the Great Western Woodlands. These eucalypt-dominated woodlands, which include mosaics of mallee, shrubland and grassland, cover nearly 160,000 km^2. This survey and previous rangeland surveys in the Sandstone, Yalgoo and Paynes Find, north-eastern Goldfields, and WA Nullarbor regions (Figure 6.2) complete mapping to a scale of 1:250,000, and describe biophysical features over the Great Western Woodlands, except for the southernmost extremities.

Major towns are Coolgardie, Kalgoorlie and Boulder in the central north, Kambalda in the centre and Norseman in the central south. Other areas of habitation separate from pastoral leases and mine sites include the roadhouses and historic town sites of Balladonia, Broad Arrow, Bullabulling, Koolyanobbing, Ora Banda, Widgiemooltha and Yellowdine. Town commons and freehold parcels make up less than 1% of the survey area. The Cundeelee Aboriginal Reserve in the east occupies about 1,147 km^2 (<1% of the area). Most of the survey area (57%) is composed of large tracts of unallocated Crown land which accounts for about 86,064 km^2.

Nature conservation areas cover about 30,561 km^2 (20%) and consist of the Boorabbin, Credo, Frank Hann, Goldfields Woodlands, Goongarrie, Jaurdi and Peak Charles national parks; the Dundas, Jilbadji, Kurrawang, Mount Manning Range and Queen Victoria Spring nature reserves; plus smaller timber reserves, conservation parks and small nature reserves.

Pastoralism is the most extensive land use in the area. Twenty-eight pastoral leases fall within the survey area and collectively occupy about 29,107 km^2 (19%). Mining occurs as isolated areas of intense activity particularly along greenstone belts and, to a lesser extent, ironstone ranges. Gold, nickel, copper, cobalt, iron and lithium are the major minerals being extracted. The region is heavily mineralised and extensive exploration has been undertaken.

This bulletin provides a regional inventory and descriptive reference of land resources in the southern Goldfields to accompany a land system map. It provides information on survey methods, climate and landscape evolution. The characteristics and distribution of soils, vegetation and habitat type ecology, and land systems are described in detail. Within the survey area there are: 69 WA Soil Groups, belonging to 12 Soil Supergroups (Table 5.1); 88 habitat types split between 13 groups (Table 6.5); and 101 land systems grouped into 41 broad land types (Volume 2, Table 7.2).

Information and descriptions of soils, habitat types and land systems were derived from 663 detailed inventory sites and 4,608 traverse assessment sites (Figure 2.3 and Figure 2.4). Within pastoral leases, 3,737 traverse assessment sites were assessed for rangeland condition. Of these, 26% had rangeland condition in good condition, 32% in fair condition and 42% in poor condition.

Climate

Over the Cenozoic Era, the survey area has been moving north, from near-polar latitudes towards its current mid-latitude position. Over the same period, the globe has transitioned from greenhouse to icehouse conditions. Paleoclimate evidence from the survey area and nearby is consistent with this climate transition. The local paleoclimate has been affected by marine transgressions that were influenced by tectonic motions. Over millions of years, the climate of the southern Goldfields has changed from humid, warm to cool temperate with periods of freezing conditions, to its current dry temperate to arid climate.

The present climate of the survey area is largely controlled by the seasonal location of the southern hemisphere subtropical high-pressure ridge, which moves over the area each winter and south in summer. The west, south-west and south are extra-dry Mediterranean and have hot, dry summers and cool, wet winters. They experience 7 to 8 dry months a year. The central part is semidesert Mediterranean and has hot and dry summers and short cold winters that deliver most of the rain. It experiences 9 to 11 dry months a year. The north-east has a non-seasonal dry desert climate with high evaporation and low precipitation.

Landscape evolution

Geology

Southern WA and the southern Goldfields survey area straddle the continental crust of the south-eastern part of the Archean Yilgarn Craton and the Proterozoic Albany-Fraser Orogen (Figure 4.1). The Yilgarn Craton is an ancient and stable shield that represents some of the oldest rocks preserved on Earth. The Albany-Fraser Orogen is sutured to the south-eastern margin of the Yilgarn Craton and occupies the south-east of the region and the survey area. It represents the initiation of modern-style plate tectonics with extensive reworking of Yilgarn crust and lateral accretion of new rocks by rifting, deposition, compression and subduction during the Proterozoic Eon. The survey area's southern and eastern margins contain Phanerozoic sedimentary rocks formed when climate, tectonics and isostasy caused ice, rivers and oceans to erode terrestrial surfaces and deposit materials on the inundated continental basement. Marine incursions during the Cenozoic Era significantly modified much of the south-east of the survey area, eroding prior surfaces and depositing calcareous materials on which new soils have formed.

Geomorphology

The survey area is characterised as an extensive plateau to the west and etchplain of low relief to the east. The area has deeply weathered regolith, infrequently punctuated by emergent outcrops and linear ranges of resistant rocks. The predominant landforms are broad, level or gently inclined plains with loamy surfaces and plains with gravel mantles, gently undulating sandplains, and occasional low hills and ridges on basalt, granite, greenstone and metasedimentary rocks.

Drainage systems are ephemeral. The broad valleys have progressively become occluded by terrestrial sediments and are now punctuated by playas and salt lakes that developed as the climate became more arid. The survey area encompasses most or all of the following salt lake systems (from north to south): Lake Rebecca; Lake Yindarlgooda and Lake Roe; Hammersley Lakes; Lake Deborah and Lake Seabrook; Lake Lefroy, Lake Randall, Lake Rivers, Lake Harris; Lake Cowan and Dog Lake; Lake Hope and Lake Johnston; Lake Dundas; Lake Tay; and Lake Sharpe. Windblown material – predominantly sand – is eroded from lake beds and deposits as sand sheets and lunette dunes at the south-east margin of playas. Ponton Creek in the north-east infrequently drains an extensive catchment whose valleys contain many salt lakes from within and to the north of the survey area. Other major catchments of the area lack terminal rivers, and upper catchment tributaries flow infrequently.

Southern and eastern margins of the survey area contain level to gently undulating marine sedimentary plains and wave ravinement surfaces with sandy quartz and calcareous sediments locally reworked by eolian processes. The north-east margin of the survey contains the south-western extremity of an extensive sandy desert comprising linear dunes formed from reworked Mesozoic sediments.

Physiographic regions, provinces and soil-landscape zones

This survey revises physiographic mapping of the area conducted by previous authors. We maintain the hierarchical system of the state soil-landscape mapping, adding new zone boundaries and physiographic descriptions. The survey area consists of 3 physiographic regions, which subdivide into 6 physiographic provinces (Figure 4.6). Most of the survey area lies within the Western Region – the 4 provinces of the Western Region are the predominant Kalgoorlie and Stirling provinces in the centre and south, respectively, and the marginal Avon and Murchison provinces in the south-west and the north, respectively. The eastern extremity of the survey area lies within the Great Victoria Desert Province of the Sandy Desert Region in the north-east, and the Nullarbor Province of the Central Southern Region in the east.

The physiographic provinces subdivide further into 17 soil-landscape zones (Figure 4.7). These zones are defined on geologic and geomorphic criteria that reflect broad erosion and deposition patterns and landscape maturity. This survey extensively revised the soil-landscape zonation of the region. We identified 4 new soil-landscape zones, modified the extent and/or descriptions of 6 zones identified by earlier authors, and retained 7 previously identified zones. The soil-landscape zones are composed of land systems.

Land systems

A land system is defined as an area with a recurring pattern of topography, soils and vegetation. Land systems consist of smaller landforms (land units or elements), each of which has a distinct characteristic pattern visible on aerial photography and other remotely sensed images. Land systems are grouped into land types according to a combination of landforms, soils, vegetation and drainage patterns (Volume 2, Table 7.1). Within the survey area, we identified 101 land systems (Volume 2, Table 7.2), 62 of which are described for the first time and 39 have been described in adjacent surveys. The amalgamation of these land systems into 41 broad land types provides summary information and logical, colour-coded regional scale maps.

Soils

Soils are salient characteristics used to distinguish and describe land systems. Within the survey area, we identified and described 69 WA Soil Groups that belong to 12 Soil Supergroups (Table 5.1). From a landform perspective, soils are broadly considered within the geomorphic features of sandplains, stony uplands, sheetwash plains and lowlands.

Sandplains

Extensive sandplains of red and yellow deep sand soils commonly overlie granite in the north and west of the survey area. Dunefields dominated by yellow deep sand soils are present on sediments in the north-east. Ironstone gravelly soils commonly border sandplain on granite and often form breakaway scarps. In the south-west, the sandplain, having experienced a different climate and ecological history, contains ironstone gravelly soils vegetated by heath and alkaline grey sandy duplex soils vegetated by mallee.

Stony uplands

Granite domes outcrop throughout the area and are generally devoid of soil and vegetation. Stony soils and shallow and deep sand and loam soils, which are red in the north and yellow–brown in the south, surround granite outcrops.

Linear, north-north-west trending greenstone belts are common through the central and north of the survey area and are present in smaller proportion in the eastern granite terrain. Crests and hills of greenstone have stony soils, often with calcareous subsoil. Lower slopes have red loamy and clayey soils that are usually calcareous. Lower slope red loamy soils contain abundant iron-rich nodules and a calcareous subsoil.

In the south-east and on large Proterozoic dykes, the crystalline rocks form prominent ridges and hills, such as Jimberlana Hill, Fraser Range and Southern Hills. These rocky protrusions have shallow rocky soils on their crests. Their upper slopes have red shallow loam soils, which yield to red loamy earth and calcareous loamy earth soils on mid-slopes and then to red clay soils on lower slopes and cracking clay soils in drainage foci.

Rocky hills commonly generate fresh run-off and form valleys with fresh or brackish minor ephemeral rivers and terminal swamps and lakes that have cracking clay soils and little salt accumulation.

Sheetwash plains

Run-off from rocky hills flows via sheetwash over broad, gently undulating plains and coalesces in broad valley floors characterised by heavy red loamy soils (often calcareous) and red–brown clay soils with calcareous subsoils. Sheetwash plain soils take 2 distinctive forms. In the north, sheetwash plains contain red loamy earth and red–brown hardpan shallow loam soils that are vegetated by *Acacia aneura* (mulga). In the south, sheetwash plains contain alkaline red loamy duplex, red loamy earth and calcareous loamy earth soils vegetated by eucalypt woodland.

Across the south-east of the survey area, calcareous sandy earth and alkaline sandy duplex soils, often with calcrete concretions and hardpans in subsoil, have developed on calcareous sediments that were deposited during marine transgressions. Further north on greenstone, calcareous loamy earth and calcareous heavy loam soils have loamy surface textures underlain by calcareous clay subsoil, which often contain calcareous concretions.

Lowlands

Throughout the survey area, major trunk valleys contain salt lakes with salt lake soils and saline soils that are devoid of vegetation. Salt lakes are irregularly inundated, during which surface sediments are sorted to provide sand that blows after the lakes dry out. The wind-eroded materials deposit mostly to the south-east of the lake systems, forming extensive calcareous sand dunes and sand sheets of yellow deep sand, calcareous deep sand and calcareous gravelly deep sand soils. Depending on the hydrological characteristics of the system, gypsum dunes and clayey calcareous material also deposit next to the lakes as small crescent-shaped lunettes and dunes.

Lowlands fed by rocky interfluves and in the upper catchments of major valleys have fresh or brackish terminal swamps, which commonly contain self-mulching and hard cracking clay soils and occasionally hard non-cracking clay soils.

Vegetation and habitat type ecology

This survey augments vegetation mapping of the area while retaining concepts and descriptions identified by other authors who described botanical provinces and biogeographic regions. Importantly, the Vegetation and habitat type ecology chapter describes ecological processes by summarising the key elements of vegetation, landform, geology, geomorphology and soil descriptions detailed in other chapters. It thus provides a sufficiently detailed but broad overview to stand alone; readers can glean further details from other chapters.

Botanical provinces and bioregions

Most of the survey occurs within the South-western Interzone Botanical Province (Figure 6.1). The north-east portion falls between the Murchison and Great Victoria Desert regions in the Eremaean Botanical Province and the southern portion is within the Mallee region in the Southwest Botanical Province. Vegetation provinces refer to areas identified in historic vegetation mapping but have largely been replaced by the current Interim Biogeographic Regionalisation for Australia (IBRA) or 'bioregion' mapping system. Most of the survey area lies in the Coolgardie bioregion of the IBRA system. Some of the south and south-west is within the Mallee bioregion. The west is bordered by the Avon Wheatbelt bioregion. The central northern and north-eastern portions include the southernmost Murchison and the Great Victoria Desert bioregions, respectively. The Nullarbor bioregion borders the east.

Plant species are predominantly those found in the Coolgardie bioregion mixed with those in the Mallee bioregion (in the south and south-west) and the southernmost Murchison and Great Victoria Desert bioregions (in the north-east). During the survey, 865 species of vascular plants were recorded. The major families encountered were Asteraceae (37 species, genus *Olearia*), Chenopodiaceae (64 species, genera *Atriplex*, *Maireana*, *Rhagodia*, *Sclerolaena*, *Tecticornia*), Fabaceae (120 species, genera *Acacia, Senna*), Myrtaceae (181 species, genera *Eucalyptus*, *Melaleuca*, *Verticordia*), Poaceae (49 species, genera *Austrostipa*, *Enneapogon*, *Eragrostis*, *Triodia*), Proteaceae (62 species, genera *Banksia*, *Grevillea*, *Hakea*) and Scrophulariaceae (52 species, genus *Eremophila*).

Within the southern Goldfields, broad vegetation communities are best described in the context of geologic and geomorphic criteria. This facilitates the mapping and analysis of these land system characteristics.

Northern and western sandplain communities

The north of the survey area is characterised by large areas of sandplain that form the southern extremities of more extensive sandplain to the north, outside the survey area. In the north-west, sandplains of yellow and occasional red sands support mallee woodland over *Triodia* spp. (spinifex), and acacia–allocasuarina thickets on gravelly sand sheets. Downslope of sandplain lies sheetwash plains with red loamy soils that support woodlands of *Acacia aneura* (mulga) and *Eucalyptus loxophleba* subsp. *lissophloia* (smooth-barked York gum) with acacia thickets. The sheetwash plains transition downslope into *Eucalyptus salmonophloia* (salmon gum) and *E. salubris* (gimlet) woodlands with some mallee and acacia scrub on red loamy duplex and clay soils. Northwards, sandplain soils become red and the vegetation transitions into predominantly spinifex grassland.

These north-western sandplains and surrounds are punctuated by iron-rich hills and undulating plains that include the prominent banded iron formation of Bungalbin (Helena and Aurora Range). On the range and nearby, woodlands with *Eucalyptus capillosa* (inland wandoo) and *E. ebbanoensis* subsp. *ebbanoensis* over grass tussocks of *Neurachne annularis* are common, with *Banksia arborea* (Yilgarn dryandra) occurring on the ferruginous ridge crests. Other banded iron formations support allocasuarina scrub thickets. The broad valley floors between uplands support *E. salmonophloia* and *E. salubris* woodlands over chenopod-dominated understoreys.

Sandplains of red sand and sandy earth soils on granite continue along the survey's central north. These are interspersed with occasional mesas and stony plains of granite and greenstone intrusions with hardpan wash plains draining to salt lakes. The vegetation is dominated by *A. aneura* shrublands with spinifex grasslands and some halophytic shrublands on stony uplands. Southwards, the *A. aneura*-dominated shrublands transition to eucalypt–mulga woodland as eucalypts become progressively dominant and red loamy duplex soils replace the red–brown hardpan shallow loam soils of the sheetwash plains. Halophytic shrublands on saline soil dominate the lake country.

Soils and vegetation in the north-east corner of the survey area are influenced by proximity to the south-western extremity of the Great Victoria Desert. Although most of this desert contains red sand dunes, the south-western edge in the survey area contains yellow sandplains over granite whose vegetation is dominated by mallees (*Eucalyptus concinna*, *E. youngiana*), mulga shrublands and spinifex grasslands, and *Eucalyptus gongylocarpa* (marble gum) increases in prominence. Halophytic shrublands are restricted to the footslopes of mesas, saline stony pavements and playas. In the desert, the vegetation on yellow deep sands is dominated by spinifex grasslands with mallee (*Eucalyptus youngiana*), scrub on dunes, and patches of *A. aneura* and *E. gongylocarpa* in swales. To the south-east of the desert, the deep yellow sandplains become shallow sand sheets covering gently undulating calcareous plains that overlie the Proterozoic gneiss and volcanic rocks of the Albany-Fraser Orogen. Here the vegetation is dominated by *E. concinna* (Victoria Desert mallee) woodland over *Triodia scariosa* (spinifex), and some *A. aneura* shrublands; soils are often calcareous gravelly sandy earth or calcareous shallow loam.

The west of the survey area is also dominated by gently undulating granite-derived sandplain consisting of yellow sand and sandy earth soils, interspersed with subdued uplands and isolated greenstone hills and granite inselbergs. While there are patches of spinifex with emergent mallees in the north, this vegetation transitions south to become dominated by acacia–allocasuarina–melaleuca scrub thickets. The vegetation transitions again further south into mallee-dominated heathlands. Dissecting the sandplains are broad valleys draining to chains of salt lakes. Colluvial slopes and valley floors are dominated by mixed eucalypt woodland with groves of melaleucas. Halophytic shrublands are largely restricted to poorly drained, saline flats and the margins of playas and salt lakes.

Central greenstone terrane woodlands and shrublands

The centre of the survey area is characterised by greenstone hills and ranges, granitic hills and rises and the intervening broad, undulating to level plains between upland areas. Acacia shrublands (*Acacia acuminata*, *A. burkittii*, *A. quadrimarginea*) regularly dominate the hills, ranges and stony rises, and the plains support woodlands dominated by *Eucalyptus salmonophloia* and/or *E. salubris* over chenopod- or eremophila-dominated understoreys. Chenopod-dominated understoreys are commonly associated with alkaline red loamy duplex soils that are usually calcareous at depth. In contrast, eremophila-dominated understoreys tend to occur on red loamy earth and red loamy duplex soils, which are not alkaline or only alkaline at great depth. Distinct soil and vegetation communities form in accumulation zones. Fresh and brackish swamps have cracking clay soil vegetated by *Duma florulenta* (lignum) and are surrounded by *E. salubris* woodland. Where salts accumulate in the lowest landscapes, salt lakes and playas with diverse, salt-tolerant communities occur on calcareous clay loam, red–brown non-cracking clay or hard cracking clay soils. Subsoils are usually saline and often contain gypsum. Adjacent to, and derived from the salt lakes, are elevated eolian lunettes and sand sheets with yellow deep sand and calcareous sandy earth soils. These support mallee eucalypts over spinifex and/or sclerophyllous shrubs.

The lower central eastern portion of the survey area is characterised by very gently undulating plains with a thin veneer of fine, sandy, shallow marine sediments over an Archean–Proterozoic suture zone. Soils are dominated by calcareous sediments. These plains predominantly support *Eucalyptus oleosa* subsp. *oleosa* (giant mallee) and *Melaleuca* spp. (boree) woodland over *Cratystylis conocephala* (false bluebush) dominated understorey. Infrequent hills and rises of shallow crystalline basement rock support acacia shrublands, and occasional outcrops of spongolite sedimentary sequences support eucalypt woodland over sclerophyllous shrubs. Drainage is subdued and occluded, and salt lake chains support chenopod communities along lacustrine surfaces, and mallee eucalypts over spinifex occur on lunettes and sand sheets.

Southern mallee woodlands

The south-west border of the survey area occurs along the edge of the South-eastern Zone of Ancient Drainage. This zone is characterised by gently undulating plains that form the headwaters of exoreic salt lake chains in the main valleys. These uplands have duplex and ironstone gravelly soils and areas of prominent granitic outcrop. Mallee woodland is common to alkaline sandy duplex soils, and proteaceous scrub–heath occurs on various ironstone gravelly soils and pale or yellow deep sand soils. The valley floors support woodlands of *Eucalyptus salmonophloia, E. salubris* and *E. longicornis* or *E. melanoxylon* (morrel) and halophytic shrublands.

The south-west southern region of the survey area is characterised by occluded salt lakes with extensive eolian sandy dunes that are vegetated by diverse mixed heath. Lakes are surrounded by interfluves of gently undulating plains with sandy duplex soils that overlie deeply weathered granite, and diverse mallee low woodland including *Eucalyptus eremophila* (tall sand mallee), *E. eremophila* subsp. *eremophila* (sand mallee) and *E. platycorys* (Boorabbin mallee).

Most of the survey's central southern area is characterised by level to gently undulating plains of Tertiary sediments over Proterozoic granites and gneisses. The vegetation comprises woodland mosaics of *Eucalyptus oleosa* subsp. *oleosa*, *E. flocktoniae* subsp. *hebes*, *E. urna* and *E. salmonophloia*, with mallee and scrub or heath. Soils are predominantly alkaline sandy loam and sandy duplex soils whose sand fraction is typically fine-grained. Drainage tracts are few and indistinct in the north and contain infrequent closed depressions and drainage foci that become increasingly common to the south (outside the survey area) and are fringed by myrtaceous and proteaceous thickets.

Fraser Range and surrounding woodlands and shrublands

In the south-east of the survey area are the prominent rolling hills and rises associated with the Proterozoic metamorphic rocks of Fraser Range. These stony hills support scattered *Allocasuarina huegeliana* (rock sheoak) and *Pittosporum angustifolium* (native willow) with *Dodonaea adenophora* and *D. microzyga* low scrubland on shallow and stony soils, with the lower slopes supporting mixed mosaics of dodonaea low scrub or spinifex with mallee. The adjacent plains support eucalypt forest typically consisting of *Eucalyptus dundasii* (Dundas blackbutt) and groves of melaleuca or *E. oleosa* subsp. *oleosa* woodland over understoreys dominated by *Atriplex* (saltbush) or *Cratystylis conocephala* on loams and clays, which are often calcareous.

Between Fraser Range and Balladonia roadhouse in the far south-east, the area is typified by undulating plains on calcareous Eocene sediments over Proterozoic granite and gneiss of the Albany-Fraser Orogen. The plains are infrequently punctuated by rock outcrop and closed depressions which may sometimes contain small, occluded playas. Calcareous soils support a woodland mosaic of *Eucalyptus oleosa* subsp. *oleosa*, *E. flocktoniae* subsp. *hebes* and *E. urna*, or *E. transcontinentalis* (redwood) woodland over either mixed scrub or chenopod shrub understoreys. *E. salubris* is common on heavier-textured soils.

Woodlands along the western edge of the Nullarbor

The eastern border of the survey area is closely aligned with the south-western margin of the Nullarbor Province and the western extent of the Eucla Basin. It is characterised by undulating calcrete plains on Eocene–Miocene limestones, and has mainly gravelly calcareous soils and some red loamy earth soils. The vegetation in the north predominantly consists of mosaics of *Eucalyptus gracilis* (white mallee) and *E. oleosa* subsp. *oleosa* (giant mallee) woodlands over mixed scrub or chenopod understoreys; *Acacia papyrocarpa* (western myall) and/or *Casuarina pauper* (black oak) woodlands over chenopods; or *Eucalyptus concinna* and *E. oleosa* subsp. *oleosa* woodland over spinifex. To the south the vegetation is predominantly *E. oleosa* subsp. *oleosa*, *E. flocktoniae* subsp. *hebes* and *E. urna* woodlands with scrub and occasional saltbush shrubland.

Habitat type ecology

Interrelated physical environs and plant communities are defined by habitat types, which are combinations of landforms, soil types and plant communities. Habitat types are clustered into broader groups to aggregate ecologically similar types. Habitat types within a ‘habitat type group’ are in topographically comparable positions. Within the survey area, 88 habitat types split between 13 habitat type groups were identified (Table 6.5). Forty-nine habitat types are described for the first time.

Disturbance effects

Most habitats appear resilient despite modification by disturbance across a variety of scales. The habitats are adapted to local-scale, commonplace, natural disturbance events such as flooding, hail and windstorms, which reduce protective vegetative cover but increase water and nutritional resources in the short term, and provide additional niches in the form of windfall and hollows in the longer term.

Recent human disturbances include:

- regional climate change impacts
- change from traditional mosaic burning by Indigenous people to landscape-scale wildfires
- introduction of exotic plant species
- wood harvesting
- increased grazing pressure caused by a combination of exotic herbivores (e.g. sheep, cattle, goats) and increased fresh water supplies to sustain larger populations of native and exotic herbivores
- changes to surface water flow regimes causing localised droughting downslope of infrastructure such as tracks, exploration gridlines and fencelines, particularly in sheetwash plain landscapes
- increased soil acidity and consequent vegetation decline of the eucalypt woodland habitat surrounding gold roasting plants, which generate acidic emissions, north and south of Kalgoorlie
- localised increase in saline landscapes caused by use of saline groundwater for dust suppression on transport routes during mining operations.

The loss of traditional low-intensity patch burning practices by First Nations Australians has contributed to the accumulation of fuel loads through many habitats, resulting in extensive intense wildfires. Throughout the region fire-sensitive vegetation communities, such as those containing *Acacia aneura* (mulga), *A. papyrocarpa* (western myall), *Atriplex vesicaria* (bladder saltbush) and *Eucalyptus salubris* (gimlet), are at risk from increased fire intensity and frequency. Many fire-sensitive vegetation communities need long intervals between fires to reach maturity. Natural landscape barriers protect some communities, facilitating the development of long fire-return intervals. Granite domes and salt lake systems provide such protection to leeward eucalypt woodlands and chenopod shrublands by buffering against fire and interrupting landscape connectivity. Increasing maturity within eucalypt woodlands reduces the likelihood of burning because of the height, openness and structure of the tree canopy in addition to the scattered character and height of the understorey, discontinuous litter coverage and large patches of bare ground. Elsewhere, self-reinforcing fire–vegetation–soil feedbacks influence vegetation mosaics, allowing communities such as mulga shrubland to persist within the fire-prone matrix of *Triodia* spp. (spinifex) grassland. Modern fire regimes in association with effects of climate change and increases in understorey biomass threaten the longevity of fire-sensitive communities.

The range extension of exotic grass species, such as *Cenchrus ciliaris* (buffel grass), in response to changing climatic conditions, and the resurgence of native tussock grasses, in response to reduced grazing pressure following the decrease in sheep numbers since the early 2000s, may improve the spatial connectivity within eucalypt woodlands. These changes may increase their susceptibility to fire as climatic conditions influence fuel accumulation and flammability, thereby overcoming fuel conditions which usually constrain fire spread. Increasing fire frequency could significantly alter the species composition of fire-sensitive woodlands as they struggle to reach floristic maturity.

Introduced plant species, other than grasses, are also having local impacts. Colonisation of disturbed and degraded habitats by exotic perennial herbs, such as *Asphodelus fistulosus* (onion weed) and to a lesser extent *Salvia verbenaca* (wild sage), compete strongly with pastorally palatable species and significantly reduce pastoral productivity. Although *A. fistulosus* prefers sandy alkaline soils, its ability to readily colonise disturbed sites enables it to become well established along roadsides and railway lines, facilitating spread into a range of other habitats, particularly those in the Fraser zone and Nullarbor Province. Considered primarily a weed of disturbed locations, it is now common and naturalised throughout western WA and other parts of Australia. Being well adapted to arid conditions, *A. fistulosus* requires attention to develop understanding of its ecology to provide strategies for management.

Historically, wood harvesting significantly affected the eucalypt and mulga woodlands. Extensive clear-felling for the lumber and firewood needs of the mining industry and domestic supply occurred following gold discoveries towards the end of the 1800s. Since the cessation of industrialised harvesting in most places, the woodlands have successfully regenerated from coppice and seed. Elsewhere, shrub species may have replaced eucalypts.

Impacts of pastoralism vary from lease to lease. In some areas, disturbance is insubstantial. Other areas have been considerably degraded by reduced vegetation cover, decreased species diversity, scrub encroachment, weed proliferation and erosion. The condition of some habitats preferred for grazing has declined – the extent of palatable species has been reduced or totally lost. Some locations affected by historic overgrazing have undergone a step-change in ecological state due to altered species composition, soil loss or both stressors combined.

Some habitats – such as greenstone ranges, granite domes, drainage foci, sand banks and dunes associated with lake systems and sandplains – are known to be potential locations for flora needing conservation. In particular, breakaway plateaus and banded iron formations, such as Bungalbin (Helena and Aurora Range), support a disproportionately high number of declared rare and priority species. Throughout the region, the most likely threat comes from mineral exploration and mining. Areas containing species of special conservation value need to be carefully managed.

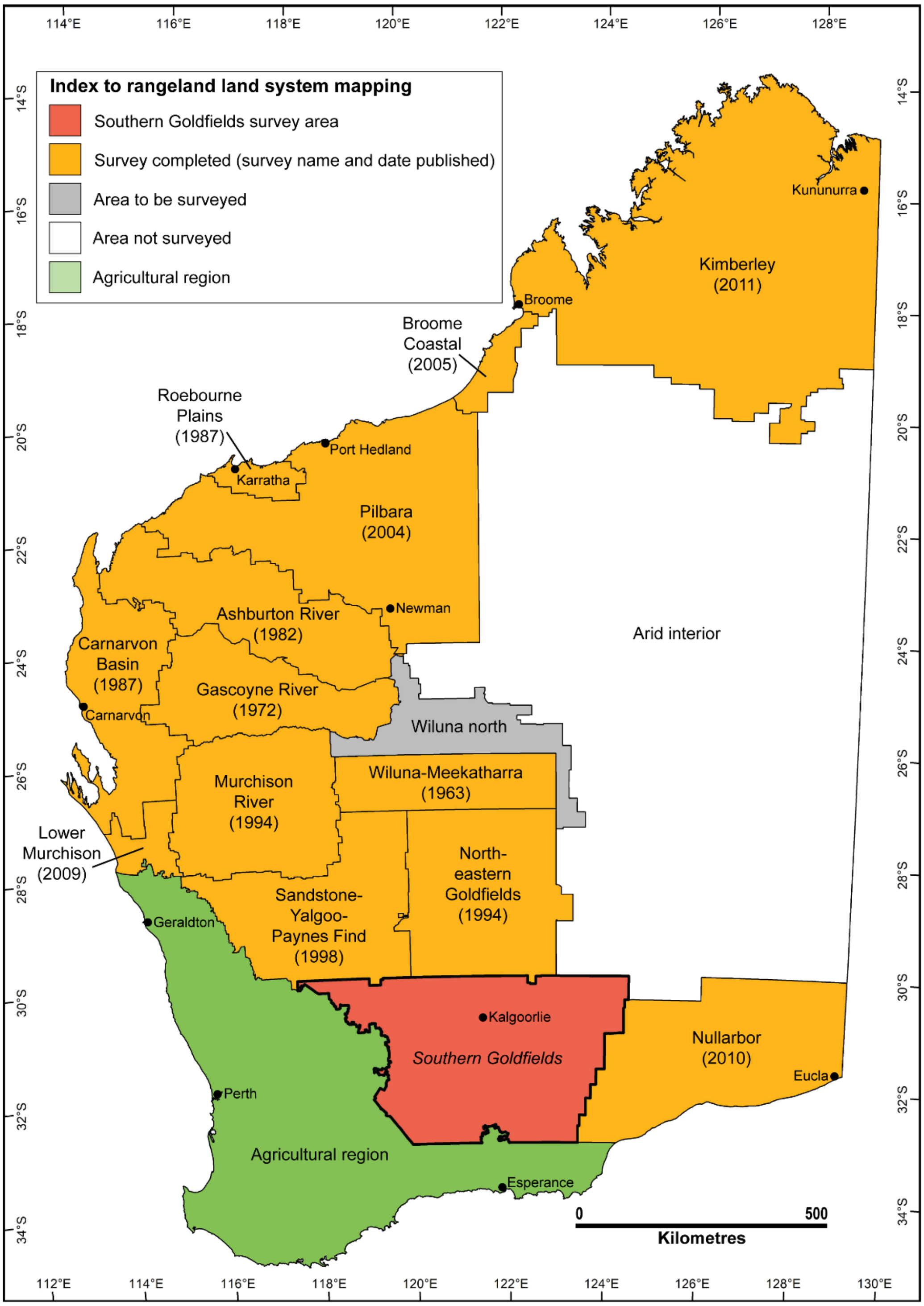
Another threat to declared rare and priority species comes from uncontrolled goat grazing. Goats' ability to migrate across large areas and their preference for upland habitats can result in considerable damage to sensitive vegetation communities. While many plants are typically not palatable to sheep and cattle, or they grow in areas frequently inaccessible to them, the mobility and varied dietary preferences of goats can lead to uncontrolled grazing in areas supporting sensitive vegetation communities.

Soil erosion mostly occurs along artificial water-concentrating features like tracks, fencelines and around dams on valley floors. In some areas, overgrazing has affected soil stability and, in association with poorly placed infrastructure, resulted in local erosion. However, the most critical land management issues in the region are those associated with the inevitable interferences from exploration and mining activity because their tracks and gridlines alter surface water flows permanently, despite the intention of proponents to place this infrastructure temporarily. While surfaces with extensive stony mantles are typically not susceptible to erosion, these surfaces can erode when they are disturbed by construction of exploration tracks and drill pads on landforms with gradients. Other erosion issues arise where sheet flows are diverted or concentrated across habitats with texture contrast (duplex) soil types, particularly those on sloping landforms. This often results in erosion along the tracks and droughting of communities downslope. The margins of salt lakes are also particularly sensitive. Sandy lake margins, banks and dunes are susceptible to wind erosion if vegetative cover is lost by any process (including fire). Such sites, once eroded, are difficult to rehabilitate.

1 Introduction

Rangeland surveys

This rangeland resource survey of the southern Goldfields region and Great Western Woodlands of WA is the fifteenth of its type in a program of rangeland classification, mapping and resource evaluation (Figure 1.1).



Note: DPIRD's soil-landscape mapping covers the agricultural area (Schoknecht et al. 2004). The Kimberley and Nullarbor regions include an amalgamation of successive rangeland surveys.

Figure 1.1: Index to rangeland survey areas and land system mapping in Western Australia

Rangeland surveys have been conducted in WA since the 1950s when they were commenced by CSIRO (Christian and Stewart 1953). The land system approach to mapping country types has been widely used since the first survey. These were initially conducted by CSIRO (Speck et al. 1960; Mabbutt et al. 1963; Speck et al. 1964; Stewart et al. 1970). Later surveys were undertaken by the Department of Agriculture under various names (now DPIRD), and Department of Lands and Surveys, after being commissioned by the Pastoral Lands Board of WA. These covered the Gascoyne River catchment (Wilcox and McKinnon 1972); the West Kimberley (Payne et al. 1979); the east of the WA Nullarbor Plain (Mitchell et al. 1979); the Carnarvon Basin (Payne et al. 1987); the Ashburton River catchment (Payne et al. 1988); Roebourne Plains (Payne and Tille 1992); the Murchison River Catchment (Curry et al. 1994); the north-eastern Goldfields (Pringle et al. 1994); Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998); the Pilbara region (Van Vreeswyk et al. 2004); part of the Broome Shire (Cotching 2005); the lower Murchison River area (Hennig 2009); the entire WA Nullarbor region (Waddell et al. 2010); and the Kimberley region (Payne and Schoknecht 2011).

The survey area

An area of about 151,753 km^2 was surveyed in the southern Goldfields, extending from latitude 30°00'S in the north to 33°00'S in the south. The western and eastern borders are variable because they align with various cadastral boundaries. The western survey border, which in part follows the State Barrier Fence, demarcates cleared agricultural land from the intact, western extent of the Great Western Woodlands. The eastern border abuts the westernmost Nullarbor pastoral lease boundaries, except for the north-easternmost and south-easternmost edges which continue into unallocated Crown land (Figure 1.2).

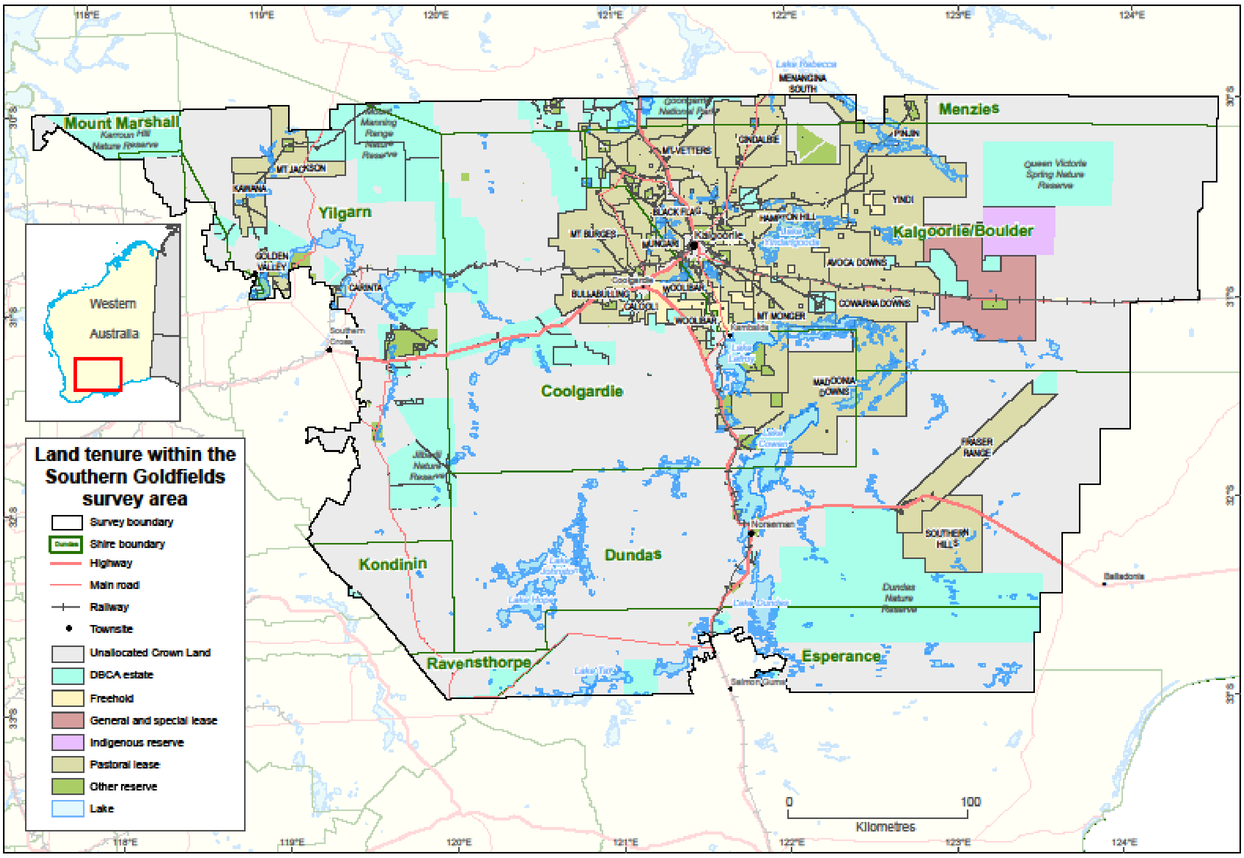


Figure 1.2: Land tenure within the southern Goldfields survey area

The area is characterised by large, linear playa (salt) lake chains in valley floors. There are no major river systems, though in the survey's north-east, the Ponton Creek infrequently drains an extensive salt lake system consisting of many playas from within and to the north of the survey area. It is a major ephemeral creek that only flows after playas overflow following heavy rainfall, and terminates at the ephemeral Lake Boonderoo outside the survey area in the Nullarbor region. Significant endoreic lake systems within the survey area linked to Ponton Creek include Lake Lefroy, Lake Yindarlgooda and the southern extent of Lake Rebecca. Other large lakes include the southward flowing Cowan and Dundas, the westward flowing Lake Deborah in the north-west, and the occluded lakes in the south-west (Hope and Johnston lakes) and south (Sharpe and Tay lakes). The region has many other less extensive salt lakes, as well as swamps and freshwater lakes, such as the regionally significant Rowles Lagoon in the central north. These drainage features form local subcatchments within a subdued relief of plains punctuated by infrequent greenstone hills, ironstone and metasedimentary ridges, and granite domes.

The limits of the southern Goldfields survey area were set by pre-existing land resource surveys undertaken by the Department of Agriculture. In the north and east, the survey area borders rangeland surveys mapped to the land system level: Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998); north-eastern Goldfields (Pringle et al. 1994); and Nullarbor (Waddell et al. 2010). In the west and south, the survey area adjoins dryland agriculture area land surveys mapped to soil-landscape subsystem and phase level: Bencubbin land resources survey (Grealish and Wagnon 1995), Southern Cross – Hyden (Verboom et al. 2004), Jerramungup (Overheu 1995) and Ravensthorpe, Esperance and Salmon Gums (Nicholas 1995). Locations of these surveys in relation to this survey are presented in Figure 1.1.

The survey area is closely aligned with the world's largest and most intact area of Mediterranean-climate woodland known as the Great Western Woodlands. These eucalypt-dominated woodlands, which include mosaics of mallee, shrubland and grassland, cover nearly 160,000 km^2. Except for the southernmost extremities, much of the survey area is within the Great Western Woodlands; the northern and eastern outlying areas occur within rangeland surveys in the Sandstone, Yalgoo and Paynes Find, north-eastern Goldfields and WA Nullarbor regions (see also Methods chapter).

The survey area includes all or part of the Coolgardie, Dundas, Esperance, Kalgoorlie-Boulder, Kondinin, Menzies, Mount Marshall, Ravensthorpe and Yilgarn shires. Major towns are Coolgardie, Kalgoorlie-Boulder, Kambalda and Norseman. Other areas of habitation separate from pastoral leases and mine sites include the roadhouses and historic town sites of Balladonia, Broad Arrow, Bullabulling, Koolyanobbing, Ora Banda, Widgiemooltha and Yellowdine. Most of the survey area is unallocated Crown land.

Areas set aside for nature conservation at the time of survey include the Boorabbin, Credo, Frank Hann, Goldfields Woodlands, Goongarrie, Jaurdi and Peak Charles National Parks; the Dundas, Jilbadji, Kurrawang, Mount Manning Range and Queen Victoria Spring nature reserves; as well as some smaller parcels of land consisting of timber reserves, conservation parks and smaller nature reserves. Pastoralism is the most extensive land use and 28 pastoral leases fall within the survey area. Mining occurs as isolated areas of intense activity, particularly along greenstone belts and, to a lesser extent, ironstone ranges. Extensive exploration has been undertaken for various minerals along the geological contact margins associated within the Albany-Fraser Orogen in the south-east of the area.

Purpose of the survey

The purpose of the survey was to provide a comprehensive description and mapping of the biophysical resources of the region.

This bulletin and accompanying land systems map are primarily intended as a reference for land managers, land management advisers and land administrators, the people most involved in planning and implementing land management practices. They will also provide researchers and others with a basic reference on landscape resources of the southern Goldfields. The survey inventory enables recognition and location of land types, land systems and landforms with particular habitat or conservation values for land use planning. Maps at scales other than that published here can be generated as required.

Monitoring of vegetation change is well established in the WA rangelands. This bulletin provides the base description of habitats (ecological site types) necessary for the strategic location of monitoring sites and provides information for the assessment of resource condition of those habitat types.

Contents of this bulletin

This bulletin provides an overview of particular aspects of the biophysical features of the southern Goldfields – there is little published information on these aspects, except for the geology, particularly where greenstones occur. Following this introduction, the Methods chapter explains the survey procedure.

The Climate and Landscape evolution chapters draw together the disparate information available and serve as an introduction to the later detailed chapters on soils, vegetation and habitat type ecology, and land systems. The Climate chapter provides a synopsis of past and present climates relevant to the survey area. The Landscape evolution chapter describes geology and geomorphology and discusses how the landforms are distributed and formed. These chapters help contextualise the evolution of the landscape and vegetation.

The remaining chapters detail the region's biophysical features relating to soils, vegetation and habitat type ecology, and land systems. They provide information on landforms, soil and vegetation at the land unit scale and, used in conjunction with the maps, provide a comprehensive description of biophysical resources. Included within these chapters are references to the impacts of certain land use practices on the soils and vegetation directed towards land managers to provide general information to assist in management planning. Though assessments of vegetation condition are primarily relevant to a pastoral context, evaluation of community composition is based on indicator species determined in intact, ungrazed states (where possible), so they do not preclude condition assessment from an ecological context. Assessments of soil condition are relevant to both pastoral and ecological contexts.

The appendices contain a summary of traverse condition ratings, summary description of soil-landscape zones, a list of soil types and lists of plant species. The species lists contain information that is too detailed to include within the main report but provides background for future research. The land system maps are a separate attachment accompanying this bulletin.

References

Christian CS and Stewart GA (1953) 'General report on survey of Katherine-Darwin Region, 1946', *Land Research Series No. 1*, CSIRO, Australia.

Cotching WE (2005) 'An inventory of rangelands in part of the Broome Shire, Western Australia', *Technical bulletin 93*, Department of Agriculture, Western Australian Government.

Curry PJ, Payne AL, Leighton KA, Hennig P and Blood DA (1994) 'An inventory and condition survey of the Murchison River catchment, Western Australia', *Technical bulletin 84*, Department of Agriculture, Western Australian Government.

Grealish GJ and Wagnon JR (1995) 'Land resources of the Bencubbin area', *Land resources series 12*, Department of Agriculture, Western Australian Government.

Hennig P (2009) 'An inventory and condition survey of the lower Murchison River area, Western Australia', *Technical bulletin 96*, Department of Agriculture and Food, Western Australian Government.

Mabbutt JA, Litchfield WH, Speck NH, Sofoulis J, Wilcox DG, Arnold JA, Brookfield M and Wright RL (1963) 'General report on the lands of the Wiluna–Meekatharra area, Western Australia, 1958', *Land Research Series No. 7*, CSIRO, Australia.

Mitchell AA, McCarthy RC and Hacker RB (1979) 'A range inventory and condition survey of part of the Western Australian Nullarbor Plain, 1974', *Technical bulletin 47*, Department of Agriculture, Western Australian Government.

Nicholas B (1995) 'Ravensthorpe, Esperance and Salmon Gums Area land resources survey' (unpublished raw data) in Department of Primary Industries and Regional Development *Map unit database*, DPIRD, Western Australian Government, accessed 17 February 2021.

Overheu T (1995) 'Jerramungup land resources survey' (unpublished raw data) in Department of Primary Industries and Regional Development *Map unit database*, DPIRD, Western Australian Government, accessed 17 February 2021.

Payne AL, Curry PJ and Spencer GF (1987) 'An inventory and condition survey of rangelands in the Carnarvon Basin, Western Australia', *Technical bulletin 73*, Department of Agriculture, Western Australian Government.

Payne AL, Kubicki A, Wilcox DG and Short LC (1979) 'A report on erosion and range condition in the West Kimberley area of Western Australia', *Technical bulletin 42*, Department of Agriculture, Western Australian Government.

Payne AL, Mitchell AA and Holman WF (1988) 'An inventory and condition survey of rangelands in the Ashburton River catchment, Western Australia', *Technical bulletin 62*, revised edition, Department of Agriculture, Western Australian Government.

Payne AL and Tille PJ (1992) 'An inventory and condition survey of the Roebourne Plains and surrounds, Western Australia', *Technical bulletin 83*, Department of Agriculture, Western Australian Government.

Payne AL, Van Vreeswyk AME, Pringle HJR, Leighton KA and Hennig P (1998) 'An inventory and condition survey of the Sandstone – Yalgoo – Paynes Find area, Western Australia', *Technical bulletin 90*, Department of Agriculture, Western Australian Government.

Payne AL and Schoknecht N (2011) 'Land systems of the Kimberley region, Western Australia', *Technical bulletin 98*, Department of Agriculture and Food, Western Australian Government.

Pringle HJR, Van Vreeswyk AME and Gilligan SA (1994) 'An inventory and condition survey of the north-eastern Goldfields, Western Australia', *Technical bulletin 87*, Department of Agriculture, Western Australian Government.

Schoknecht NR, Tille PJ and Purdie BR (2004) 'Soil-landscape mapping in south-Western Australia: an overview of methodology and outputs', *Resource Management Technical Report 280*, Department of Agriculture, Western Australian Government.

Speck NH, Bradley J, Lazarides M, Patterson RA, Slayter RO, Stewart GA and Twidale CR (1960) 'The lands and pastoral resources of the North Kimberley area, Western Australia', *Land Research Series 4*, CSIRO, Australia.

Speck NH, Wright RL, Rutherford GF, Fitzgerald K, Thomas F, Arnold JA, Basinski JJ, Fitzpatrick EA, Lazarides M and Perry RA (1964) 'General report on the lands of the West Kimberley area, Western Australia', *Land Research Series 9*, CSIRO, Australia.

Stewart GA, Perry RA, Paterson SJ, Traves DM, Wright RL, Slayter RO, Dunn PR, Jones PJ and Sleeman JR (1970) 'Lands of the Ord-Victoria area, Western Australia and Northern Territory', *Land Research Series 28*, CSIRO, Australia.

Van Vreeswyk AME, Payne AL, Leighton KA and Hennig P (2004) 'An inventory and condition survey of the Pilbara region, Western Australia', *Technical bulletin 92*, Department of Agriculture, Western Australian Government.

Verboom WH, Griffin EA and Frahmand M (2004) 'Southern Cross – Hyden land resources survey' (unpublished raw data) in Department of Primary Industries and Regional Development *Map unit database*, DPIRD, Western Australian Government, accessed 17 February 2021.

Waddell PA, Gardner AK and Hennig P (2010) 'An inventory and condition survey of the Western Australian part of the Nullarbor region', *Technical bulletin 97*, Department of Agriculture and Food, Western Australian Government.

Wilcox DG and McKinnon EA (1972) *A report on the condition of the Gascoyne catchment*, Department of Agriculture, Western Australian Government.

2 Methods

PA Waddell and PD Galloway

Land systems

The land system approach to mapping country types has been widely used in rangeland surveys in WA since the first survey in the 1950s. A land system is defined as an area with a recurring pattern of topography, soils and vegetation (Christian and Stewart 1953). Land systems consist of smaller landform units, each of which has a distinct pattern. The relative proportions of constituent landform units and their spatial arrangement relative to each other form characteristic patterns visible on aerial photography and other remotely sensed images. Once identified, it is assumed that similar patterns represent similar types of country (landscapes). The land systems are then ground-truthed during field work.

We grouped the land systems into larger mapped units called land zones, which are areas defined on geomorphologic or geological criteria, suitable for regional perspectives (Schoknecht et al. 2004). Including the land zone hierarchy in our mapping provided a spatial context for our explanations of regional geomorphology, which explain the general distribution of ecological communities, plants and soil characteristics. It enabled correlation to the mapping hierarchy devised at broad scale for physiographic mapping of the nation by Pain et al. (2011). It also allowed us to match mapping units at the edge of our maps with soil-landscape maps of the adjoining agricultural region (see Schoknecht et al. 2004) and existing mapping for the rest of WA (see Tille 2006).

Mapping datasets

We mapped most land system and zone boundaries using digital aerial orthophotographs viewed using the GIS software package GeoMedia Professional 6.1. This technology facilitated the viewing of supplementary digital datasets and visualisation at a scale of the surveyors' choosing. This flexibility greatly improved the mapping resolution and overcame some traditional limitations of mapping scale.

Georeferenced digital datasets we used to complement the mapping were: gamma radiometrics, provided by Geoscience Australia; 2006 Landsat TM satellite imagery, provided by the Australian Greenhouse Office National Accounting Scheme; digital elevation models; and 2 m contours based on 30 m resolution imagery from Geoscience Australia.

Previous Western Australian rangeland surveys mapped land system boundaries from aerial photographs (1:50,000), which adequately allowed for reproduction of topographical maps or pastoral plans at any required scale. For specific areas, we occasionally reverted to using hard copy aerial photographs (1:50,000), most notably where fire scars had obscured distinguishing landforms and vegetation in satellite imagery and recent digital aerial orthophotographs.

The minimum-sized area of land we considered mappable was about 1 km^2 in extent. Narrower areas, for example, less than 500 m, could be mapped provided they were at least 1.5 km long. This allowed mapping of long sinuous features such as hill ridges (e.g. Lawrence Land System) and significant drainage tracts (e.g. Ponton Creek).

The survey area is in Universal Transverse Mercator (UTM) coordinate system zones 50H–J and 51H–J. We used digital aerial orthophotographs to plan navigation throughout the survey area and to identify land system boundaries in conjunction with 2 m contours derived from digital elevation models, which assisted with recognising topographic relief. The aerial orthophotographs used occur totally or partially within the Balladonia, Bencubbin, Boorabbin, Cundeelee, Hyden, Jackson, Kalgoorlie, Kurnalpi, Lake Johnston, Norseman, Southern Cross, Widgiemooltha and Zanthus 1:250,000 map sheets (Figure 2.1). Digital aerial orthophotographs were dated between 2002 and 2012.

We undertook mapping at a nominal scale of between 1:2,000 and 1:50,000. To identify land system boundaries in areas where landform features were indeterminable on the digital aerial orthophotographs because of extensive bushfire scarring, we used a stereoscope with historic black and white hard copy aerial photographs from Lake Johnston: Project L46 (1971); Norseman: Project L45 (1971); Balladonia (1990); and Zanthus: Project 960026 (1997). This mapping was then digitised using GeoMedia to finalise a land system boundary.

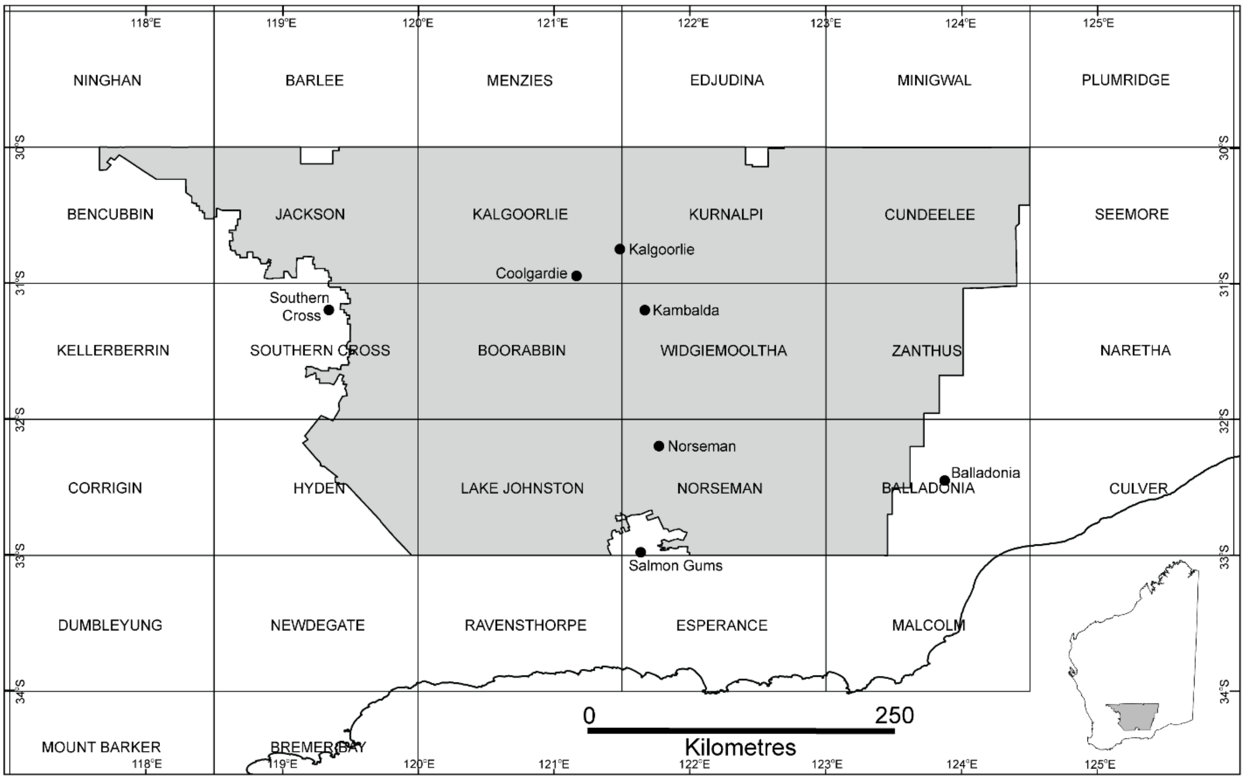


Figure 2.1: The 1:250,000 map sheets covering the survey area

Review of existing information

To help define land system boundaries, we reviewed existing sources of information on the biophysical resources of the area.

The southern Goldfields is surrounded by lands that have been surveyed and mapped by the Department of Agriculture. In the north and east, this area borders with rangeland surveys that were mapped to the land system level: Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b); north-eastern Goldfields (Pringle et al. 1994); and Nullarbor (Waddell et al. 2010). These provided knowledge of the adjacent areas, which assisted with the survey process.

In the west and south, the survey area adjoins land resources surveys of the dryland agriculture area, which are mapped to soil-landscape subsystem and phase level to conform to the CSIRO soil-landscape methodology, which for WA is described by Schoknecht et al. (2004). The Bencubbin land resources survey (Grealish and Wagnon 1995) adjoins the north-west boundary of this survey and the Sandstone, Yalgoo and Paynes Find survey area. The remaining boundary adjoins soil-landscape datasets that reside in the DPIRD soil-landscape databases. The land resources surveys contributing data to this survey were (from west to the south and then east): Southern Cross – Hyden (Verboom et al. 2004), Jerramungup (Overheu 1995) and Ravensthorpe, Esperance and Salmon Gums (Nicholas 1995). The Nicholas (1995) report contains an amalgamation of 2 types of published and unpublished surveys combined with additional spatial coverage of their own work. Nicholas collated information from dedicated soil surveys lacking landscape information from the Salmon Gums soil survey (Burvill 1988); Mount Beaumont soil survey (Scholz and Smolinski 1996); and Cascades soil survey (Scholz 1990). Nicholas also collated soil-landscape information from ‘Esperance land resource survey’ (Overheu et al. 1993) and ‘Condingup land system survey’ (Overheu 1992). The north-east and south-east corners of the survey abut unallocated Crown land, which has only a broad reconnaissance-level of soil information from the *Atlas of Australian soils* (Northcote et al. 1960−68). The various surveys, scales, purposes and names are presented in Table 2.1 and their locations in relation to the survey area are presented in Figure 2.2.

Table 2.1: Soil-landscape surveys and rangeland condition surveys surrounding and overlying the southern Goldfields survey area

ID	Project name	Project code	Project purpose	Project reliability statement
1	Arid interior of WA (Atlas of Australian Soils reconnaissance)	INTS	Broad reconnaissance, general purpose	Limited data, very broad-scale mapping
2	North-eastern Goldfields rangeland survey	NEGS	Rangeland productivity	Limited data, broad-scale mapping
3	Sandstone, Yalgoo and Paynes Find rangeland survey	SYPS	Rangeland productivity	Limited data, broad-scale mapping
4	Kambalda rangeland survey	KAMS	Rangeland productivity	Limited data, broad-scale mapping
5	Western Nullarbor rangeland survey	WNBS	Rangeland productivity	Limited data, broad-scale mapping
6	Goongarrie rangeland survey	GOOS	Rangeland productivity	Limited data, broad-scale mapping (unpublished)
7	Esperance, Ravensthorpe and Salmon Gums land resources survey (non-agricultural areas)	ERSN	Reconnaissance, general purpose	Low data quality, broad-scale mapping (unpublished)
8	Bencubbin land resources survey	MDN	Dryland (rain-fed) agricultural production	Medium data quality, broad-scale mapping
9	Esperance, Ravensthorpe and Salmon Gums land resources survey (agricultural areas)	ERSS	Amalgamation of surveys (9a–9d) for dryland (rain-fed) agricultural production	Medium data quality, broad-scale mapping (unpublished)
9a	Cascades soil survey	CAS	Dryland (rain-fed) agricultural production	No information, soil survey only with no landscape component (unpublished)
9b	Mount Beaumont soil survey	MTB	Dryland (rain-fed) agricultural production	No information, soil survey only with no landscape component
9c	Condingup land system survey	CLS	Dryland (rain-fed) agricultural production	No information (unpublished)
9d	Esperance land resources survey	ESP	Dryland (rain-fed) agricultural production	Medium data quality, detailed and precise mapping
10	Jerramungup land resources survey	JER	Dryland (rain-fed) agricultural production	Medium data quality, broad-scale mapping
11	Southern Cross – Hyden land resources survey	SCS	Dryland (rain-fed) agricultural production	Low data quality, broad-scale mapping

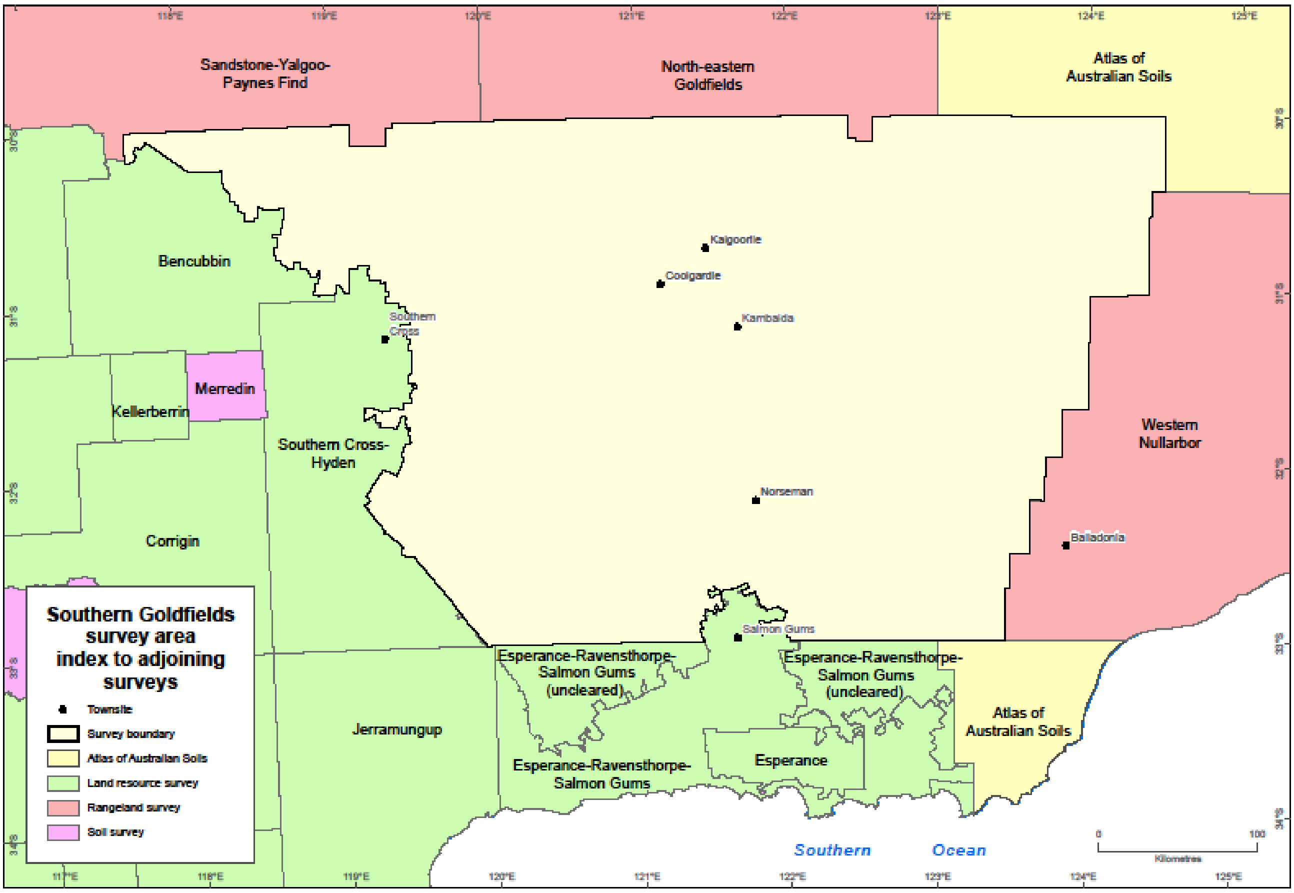


Figure 2.2: Soil and landscape surveys surrounding the southern Goldfields survey area

Within the survey area there were also 2 small areas of pre-existing land system mapping: a privately commissioned survey (Payne et al. 1998a) and a desktop mapping exercise to accompany a land-use modelling process known as the Rangeways project (Holm et al. 2002). We extensively modified and renamed the mapping from these projects to incorporate into this survey.

Tille (2006) used the hierarchical method described by Schoknecht et al. (2004) to amalgamate and transform all surveyed linework and conceptual understanding (identified above) into standardised, broad-scale ‘system’ and ‘zone’ soil-landscape map units across the state. Tille’s broad mapping and descriptive information provided valuable background to the survey area and surrounds and alerted us to existing limitations in understanding of geomorphic landforms of the region and consistency in mapping between surveys.

We gained an appreciation of the land types to be surveyed from published information on the landforms, soils and vegetation: Beard (1975, 1976, 1981); Newbey et al. (1984); Dell et al. (1985); How et al. (1988); Keighery and Hall (1992); Hall and Keighery (1993); Keighery et al. (1995); and Tille (2006). We used the 1:250,000 geological map series produced by Geological Survey of Western Australia: Balladonia (Doepel and Lowry 1970a); Bencubbin (Blight et al. 1984); Boorabbin (Hunter 1991); Cundeelee (Bunting and van de Graaff 1977); Hyden (Chin et al. 1984); Jackson (Chin and Smith 1983); Kalgoorlie (Wyche 1998); Kurnalpi (Williams 1973); Lake Johnston (Gower and Bunting 1976); Norseman (Doepel 1973); Southern Cross (Gee 1982); Widgiemooltha (Griffin 1989); and Zanthus (Doepel and Lowry 1970b).

Reconnaissance field work

Reconnaissance trips were initially undertaken between November 2008 and December 2009. This included visiting and reviewing land systems that bordered the southern Goldfields mapped during the 1988–1990 north-eastern Goldfields survey (Pringle et al. 1994) and the desktop-mapped land systems from the Rangeways project (Holm et al. 2002), which were not ground-truthed. We made 2 more reconnaissance trips in October 2010 and October 2013. During these trips, we provisionally described the habitats and land systems and undertook preliminary soil profile descriptions and vegetation collections.

The aim of the reconnaissance trips was to familiarise the survey team with northern land systems identified in the 1988–1990 north-eastern Goldfields survey, major land types and vegetation communities; to identify unfamiliar country types which would require more-intensive sampling; and to trial and finalise field methods.


Kilometres of overgrown or flooded tracks slowed and sometimes halted survey progress

Main field work

While some field work was undertaken between June 2009 and May 2011, most occurred between August 2013 and December 2016. Field work was postponed between 2011 and 2013 because survey team members were diverted to other departmental priorities. One trip in June 2017 was made to review specific areas of complexity and those missed through field trip cancellations due to rain or bushfires. In total, we made 22 trips of 1 to 2 weeks duration into the survey area. For efficient progress, we camped in different locations each night, rather than returning to designated campsites or towns, except when pastoralists offered accommodation and that location facilitated day trips.

We surveyed the area on a lease-by-lease basis, with nearby proportions of unallocated Crown land incorporated into routes. Prior to each trip, we planned routes to cover all land systems in proportion to their extent, and to ensure that any areas of particular interest, such as those with an unusual photo pattern or suspected severe degradation and erosion, were covered. We spent between 3 and 5 days on each lease depending on size, access and landscape complexity. Pastoralists were notified when we would be in their area and were encouraged to spend time with us while we surveyed their property. This provided a useful opportunity to explain the methods and purpose of the survey and to seek pastoralists’ opinions on topics such as the palatability of plant species, stocking rates of habitat types and the susceptibility of different habitats to fire and grazing.

For navigation, we used real-time GPS tracking on a Motion MC-F5V tablet to allow us to accurately determine our position on digital aerial orthophotographs while in the field. Land system identification involved digitally mapping provisional land system boundaries prior to each field trip. Once in the field, we ground-truthed the provisional boundaries, making amendments as required, using the real-time GPS tracking. We recorded the locations of flora samples, inventory and traverse sites using GPS set to Geocentric Datum of Australia 1994 (GDA94). We used the Universal Transverse Mercator or Universal Position System to provide the position format and the Map Grid of Australia to record grid coordinates as eastings and northings.

Inventory sites

We used inventory sites to describe the landforms (including geology and geomorphology), soil types and vegetation communities within each land system, and to assist in interpreting patterns identified on aerial orthophotographs and Landsat imagery. Using these salient features (i.e. landform, soil type and vegetation), we identified unique groups, referred to as habitat types. An inventory site is an area bounded by a 50 m radius of the point chosen to describe the soil. If the landform or vegetation community was smaller, only information relevant to that area was recorded. Inventory sites usually took 30 to 60 minutes to describe.

Inventory site selection typically coincided with vehicle travel along roads and tracks, or within walking distance of the vehicle for limited specific sites. Some sites were opportunistically described when a different or unusual landform, vegetation community or soil association was encountered. Not all landforms were accessible, so these lack inventory sites. Consequently, the information about land systems in Volume 2, Chapter 7 is provisional. Where possible, provisional landform information was based on similar landforms described at sites in other land systems.

Throughout the survey, we sampled 606 inventory sites (Figure 2.3). We opportunistically described one site registered outside the survey area because a road cutting provided a good view of the soil profile under vegetation common to the survey area. We also collated 57 other inventory sites into the dataset, from previous rangeland surveys that occurred within the survey area, bringing the total to 663 inventory sites. These inclusions served to increase our knowledge and consisted of 51 sites from the 1997 Kambalda area survey (Payne et al. 1998a) and 6 from the 2005 Nullarbor survey (Waddell et al. 2010).

At each site, we recorded the following information in code and note form:

- general location and background data
- physical environment
- vegetation and ecology
- soil.

Inventory site on a broad, low rise on an undulating plain

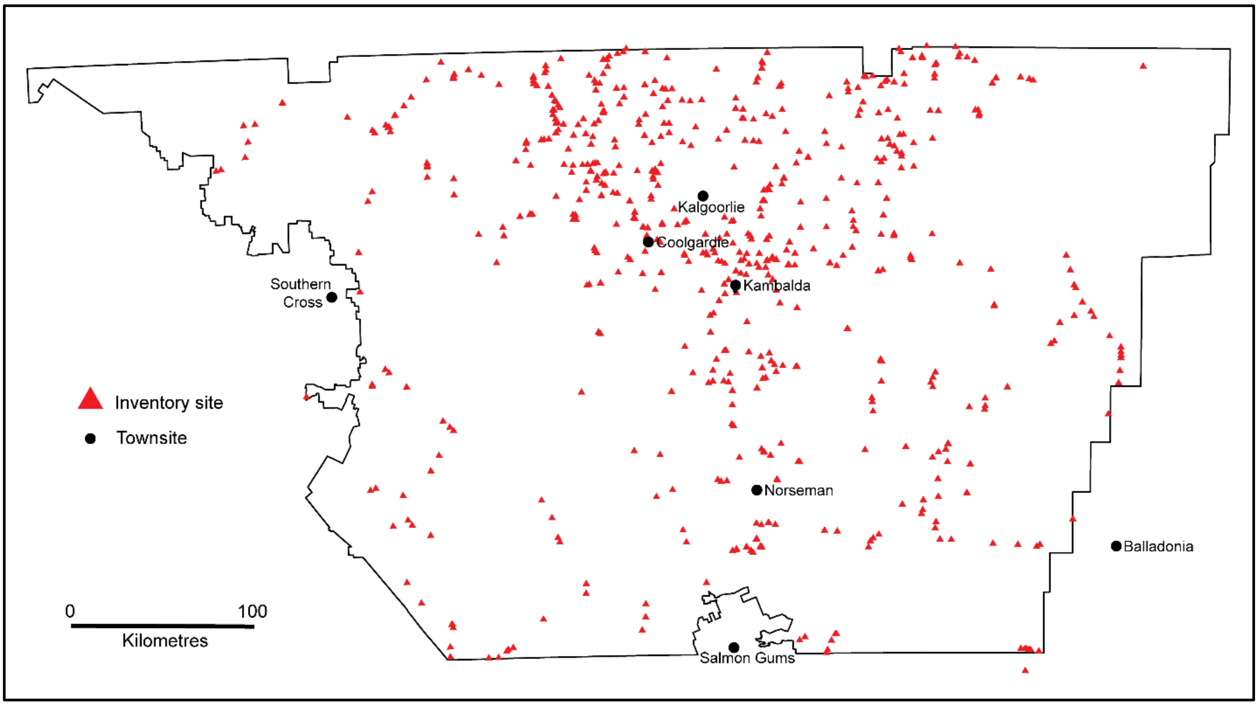


Figure 2.3: Distribution of inventory sites in the survey area

We photographed each site in a standardised way: photographs were taken atop the survey vehicle, with a board identifying the site number placed about 10 m away. We made landscape sketches and took additional notes on an ad hoc basis. We captured information and data regarding vegetation and ecology on a standard record sheet like that used by Curry et al. (1994) in the Murchison River catchment survey, and landform and soil information was captured on a standard record sheet similar to that in Stuart-Street et al. (2020). Prior to determining condition, we identified the geology using our own observations augmented by georeferenced geology maps in a GIS environment, discussed each site's landform, management and ecological stressors to ensure consistency of our assessment.

General location and background data

We collected general information to facilitate mapping, reporting and future visitation. Attributes recorded for each site were:

- site number – a sequential 4-digit number prefaced with 'I' for inventory
- land system – determined from a combination of draft rangeland mapping and visual assessment of the site and broader surrounds
- landform – a summary classification determined from detail collected during the assessment of the physical environment
- pastoral lease – determined from DPIRD lease boundary data
- location – recorded using GPS
- 1:250,000 map sheet name
- aerial photograph year, run and number
- date
- compass bearing of the site photograph.

Physical environment

We collected information about landform, geology, geomorphology agents and surface conditions to classify the site according to a limited set of rangeland land systems and land types. We used WA Geological Survey 1:250,000 surface geology maps and explanatory notes as the standard for geological attributes, and the *Australian soil and land survey field handbook*, 3rd edition (NCST 2009) as the standard for landform attributes. Attributes recorded were:

- slope aspect
- slope gradient (in percentage)
- slope length
- landform unit relief
- landform pattern
- landform element (type and site position on slope)
- relief modal slope class
- geomorphology (activity, agents and degree of activation)
- geology – described according to the 1:250,000 Geological Survey series
- site geology – determined by assessor, if different from the mapped geology
- surface mantle (abundance, shape, size and type)
- rock outcrop (abundance and type)
- type and intensity of accelerated erosion
- extent and type of surface crust
- evidence of fire.

Vegetation and ecology

We recorded all vascular plants within an inventory site. Opportunistic collections occurred outside of inventory sites to contribute to species lists. We collected unfamiliar plant species and recorded their locations for WA Herbarium staff to identify, and we completed site vegetation descriptions when this knowledge became available. We constructed a field herbarium using plant samples verified by Herbarium staff to assist with ongoing identification. Where adequate representative plant material was available and Herbarium staff considered a vouchered sample significant, it was lodged at the Herbarium. We obtained permits for flora collection from the Department of Biodiversity, Conservation and Attractions. We undertook classified assessments for the ecological parameters of habitat, foliar cover and vegetation condition and recorded the following data:

- dominant species in each stratum
- relative dominance of each stratum
- basal cover class for perennial grasses
- height class of tree stratum
- height class of tall shrub stratum
- list of perennial plant species
- list of annual species
- habitat type
- projected foliar cover (PFC) class of perennial vegetation (Table 2.2)
- vegetation condition rating.

Table 2.2: Foliar cover classes for tree and shrub strata

Foliar cover class	Projected foliar cover (%)	Foliar cover
1	≤2.5	Isolated
2	>2.5–5	Very scattered
3	>5–10	Very scattered
4	>10–15	Scattered
5	>15–20	Scattered
6	>20–25	Moderately close
7	>25–30	Moderately close
8	>30–50	Close
9	>50	Closed

Note: Classes were modified from Curry et al. (1983).

Soil

The NCST (2009) defines the standards used to describe soil characteristics. We sampled the soil by digging shallow pits with a shovel and a 50 mm diameter auger, to retrieve soil to hard rock, soil hardpan or to a depth of 1 m if no restricting layer was present. We laid samples in sequence to determine different soil layers and investigate the characteristics of each. Where possible, we also described soils from existing cuttings and quarries. In these locations, it was possible to describe in detail the subsoil structure and horizon variation, and to photograph the soil profile for a visual record of variability. Soil profiles at some sites extended to deeper than 1 m, providing valuable additional information.

We recorded change in soil features down the profile to distinguish soil layers into horizons according to NCST (2009), and to classify the soil according to the *Australian soil classification* (Isbell 2016) and the WA Soil Groups (Galloway et al. in press).

We recorded the following general information about the landform, soil and site details on field sheets like those in Stuart-Street et al. (2020):

- class – determined according to the *Australian soil classification* (Isbell 2016) and the WA Soil Groups (Galloway et al. in press)
- location of the observation – recorded using GPS
- soil surface condition
- substrate and or parent material
- soil depth class (Table 2.3; see van Gool et al. 2005)
- observation method
- surface mantle (size, type, abundance of surface gravels and stones [gibber])
- rock outcrop (type and proportion of the site)
- leaf litter (presence and proportional cover)
- biological soil crusts (presence, density and development).

We recorded the following features for each layer of soil:

- soil moisture status – determined using NCST (2009, p 186)
- horizon designation – determined using NCST (2009, pp 148–156)
- horizon boundary designation (distinctness and shape) – determined using NCST (2009, pp 199–200)
- soil texture – determined with sieved fine earth moistened to field capacity and kneaded (NCST [2009], p 161)
- soil colour – determined by comparing a moistened soil aggregate to standard Munsell soil colour charts (Munsell Color Company 2009)
- soil structure and fabric (presence or absence, size and shape of soil aggregates) – determined using NCST (2009, p 171)
- aggregate consistence – estimated by compressing a 20 mm unit of undisturbed soil (NCST [2009], pp 186–189)
- pedogenetic pans (type, structure and cementation grade) – determined using NCST (2009, pp 192–195)
- soil pH – determined using method described by Raupach and Tucker (1959), ranges identified in the Soils chapter can be converted to ratings using Table 2.4
- carbonate content – estimated by effervescence emitted on reaction of a soil sample with 1 Molar hydrochloric acid (NCST [2009], p 198)
- electrical conductivity (EC) of soil (1:5 ratio of soil to distilled water) – measured using a portable EC meter. Recorded EC was transformed by pedotransfer function to saturation paste EC (EC_e) via database algorithms using method described by Moore (1998) and expressed in mS/m (see salinity classes in Table 2.5)
- presence of coarse fragments (shape, size and abundance) – determined using NCST (2009, pp 139–143)
- presence of pedogenetic segregations (shape, size hardness, type and abundance) – determined using NCST (2009, pp 195–198)
- root density – determined using NCST (2009, p 199).

Table 2.3: Soil depth classes

Soil depth rating	Depth range (cm)
Very shallow	<15
Shallow	15–30
Moderate	30–80
Deep	80–150
Very deep	>150

Source: van Gool et al. (2005)

Table 2.4: Soil pH classes and correlation between measurement methods

Soil pH rating	pH range		
	Deionised water	Dilute $CaCl_2$	Universal indicator
Very strongly acid	<5.3	<4.2	<4.5
Strongly acid	5.3–5.6	4.2–4.5	4.5–5.0
Moderately acid	5.6–6.0	4.5–5.0	5.0–5.5
Slightly acid	6.0–6.5	5.0–5.5	5.5–6.0
Neutral	6.5–8.0	5.5–7.0	6.0–7.5
Moderately alkaline	8.0–9.0	7.0–8.0	7.5–8.5
Strongly alkaline	>9.0	>8.0	>8.5

Note: Soil pH ratings were derived from van Gool et al. (2005) using water and dilute calcium chloride solution (0.01 M $CaCl_2$) as test methods. The universal indicator values were applied to the ratings using the correlation in Rayment and Higginson (1992).

Table 2.5: Soil salinity classes

Salinity rating	Salinity value EC_e (mS/m)
Non-saline	≤200
Slightly saline	>200–400
Moderately saline	>400–800
Highly saline	>800–1,600
Extremely saline	>1,600

Source: Derived from van Gool et al. (2005)

Determining soil colour by comparing a soil aggregate against a Munsell soil colour chart

Traverse assessment sites

We followed predetermined traverse routes on digital aerial orthophotographs with draft land system boundaries draped over. We frequently made minor detours from the traverse route to check, and verify or amend, these boundaries. Traverse assessment sites were set at 1 km intervals along the traverse routes, and we recorded the geographical location of each site using GeoMedia and the inbuilt GPS on the Motion MC-F5V tablet. At each site – an area within a 50 m radius of the survey vehicle – we recorded the land system, landform and habitat type, and assessed the rangeland condition by rating the vegetation condition and the type and extent of accelerated erosion. Typically, the attributes of a habitat type had been previously described in detail at inventory sites to facilitate their identification at traverse assessment sites.

The rangeland condition was recorded as a 3-digit assessment according to the vegetation condition rating (Table 2.6) which were adapted from the Western Australian Rangeland Monitoring System (WARMS) for arid shrublands (Hacker 1988).

The ratings for vegetation condition were visual assessments, based on the assessor knowing what type of vegetation is supported on the landform and soil association. This includes an understanding of a range of attributes, such as species distribution and composition, density and cover, and the effect of disturbance events on the habitats. Assessments were also supported by information in other WA rangeland surveys and material, such as Mitchell and Wilcox (1994); Fletcher (1991, 1995); Burnside et al. (1995); Russell and Fletcher (2003); Addison (2012); and Rangelands NRM (2015). A rating of excellent or very good, good, fair, poor or very poor was given, based on the extent of induced changes from the 'natural' state of the landscape (Table 2.6). Similarly, the ratings for erosion were visual assessments which determined the dominant type of erosion, when it was present, with severity determined by estimating the area affected (Table 2.7).

Table 2.6: Criteria for assessing vegetation condition

Rating	Condition indicators
1 Excellent or very good	For the habitat type, the composition and cover of shrubs, perennial herbs and grasses is near optimal; free of obvious reductions in palatable species or increases in unpalatable species, or the habitat type supports vegetation which is predominantly unattractive to herbivores and is thus largely unaltered by grazing.
2 Good	Perennials present include all or most of the palatable species expected; some less palatable or unpalatable species may have increased, but the total perennial cover is not very different from the optimal.
3 Fair	Moderate losses of palatable perennials and or increases in unpalatable shrubs or grasses, but most palatable species and stability desirables are still present; perennial cover is less than on comparable sites rated 1 or 2, unless unpalatable species have increased.
4 Poor	Conspicuous losses of palatable perennials; perennial cover is either decreased through general loss of perennials or is increased by the invasion of unpalatable species.
5 Very poor	Few palatable perennials remain; perennial cover is either greatly reduced with much bare ground arising from loss of stability desirables, or has become dominated by a proliferation of unpalatable species.

Note: The term 'stability desirables' refers to perennial plant species that are not primarily related to grazing history. They usually only decrease in number after natural disturbance events, such as fire or hail damage. These species are usually not palatable or only slightly palatable. They are recognised for their role in maintaining soil stability and ecosystem function.

Table 2.7: Criteria for assessing accelerated erosion

Type of erosion present (dominant type recorded)		Estimate of area affected by erosion	
Rating	Erosion characteristics present	Rating	Severity of site affected
0	No erosion	0	No accelerated erosion
A	Sheeting/microterracing	1	Slight erosion (<10%)
B	Scalding	2	Minor erosion (10–24%)
C	Pedestalling	3	Moderate erosion (25–49%)
D	Rilling	4	Severe erosion (50–74%)
E	Gullying	5	Extreme erosion (75–100%)
F	Accelerated accretion of soil material		

Pastoralism is the most extensive land use in the survey area, and the changes observed from the ‘natural’ state are often attributed to the development of artificial water points and grazing by introduced stock, native herbivores and feral animals, particularly goats. Changes due to other forms of disturbance, such as altered fire regimes, mining and infrastructure, were also encountered. If a traverse assessment site occurred on an area extensively altered by mining or exploration activities, we recorded this, but did not assess the rangeland condition. Traverse assessment sites within 100 m of a water point, homestead or shearing shed were also not assessed for condition.

Occasionally, on-ground boundaries, such as boundary fences, differ from digital cadastral boundaries. On-ground deviations most likely resulted from errors that occurred during historic surveying of leases prior to the use of GPS. In these instances, the on-ground property identity was considered correct rather than digital cadastral boundaries. Also, some traverse sites occurred within other forms of land tenure that included former pastoral leases now part of conservation reserves, town commons, timber reserves, mining tenements, road reserves or Crown land, or vice versa. Some land systems in this survey do not have any traverse assessments recorded on them because they occurred solely on land not gazetted as pastoral lease, such as conservation reserves or Crown land.

We completed 103 traverse routes and recorded 4,608 traverse assessments, 3,737 of which had a rangeland condition assessment within present-day pastoral lease boundaries (Figure 2.4; Volume 2, Appendix A).

Fenceline grazing effect: left of the fence, the palatable vegetation has been removed through grazing, and right of the fence shows some indication of the original vegetation community

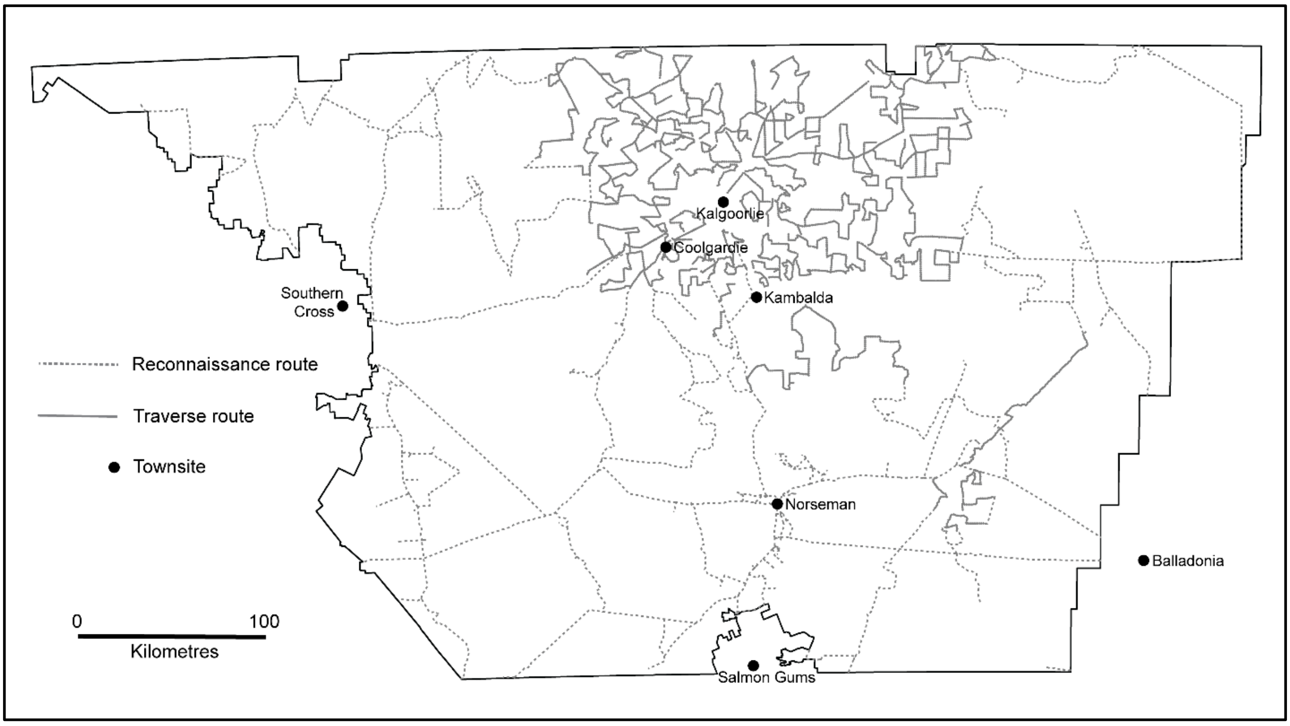


Figure 2.4: Reconnaissance and traverse routes in the survey area

Data storage

We transferred field records to the DPIRD Soil Profile Database after returning from the field, to store data securely and allow efficient data querying and analysis. The Soil Profile Database stores all records associated with site information, including site and surface conditions, landforms, vegetation structure and species present, as well as soil profile information, as described by Schoknecht et al. (2004).

Analysis of data

Traverse data

Since the traverse assessment sites were recorded using GPS, they could be referenced on the land system resource maps. This allowed traverse information, such as the pastoral lease and land system, to be cross-referenced with the location of each traverse assessment site on the map and amended if necessary.

We made summaries of the traverse assessments by sorting the data on the attributes for which information was required. For example, creating summaries of the landforms and habitat types within each land system assisted with developing the land system descriptions.

Inventory site data

The inventory site data were entered into a database and analysed to develop the descriptions of land systems, landforms, soil and vegetation. The data were linked to the resource maps to allow spatial interrogation. Inventory site data from the 1997 Kambalda area and 2005 WA Nullarbor surveys also assisted with the descriptions. In developing plant lists for vegetation communities within some habitats, we cross-checked and complemented inventory data with flora surveys in Beard (1975, 1976, 1981); Newbey et al. (1984); Dell et al. (1985); How et al. (1988); Keighery and Hall (1992); Hall and Keighery (1993); and Keighery et al. (1995).

Map production

We finalised land system boundaries using the knowledge gained during field work to reinterpret and confirm boundaries digitised using aerial orthophotographs. We reassessed land system boundaries from the Kambalda survey (Payne et al. 1998a) by using newly available spatial data (e.g. radiometrics, digital elevation data) and aerial orthophotographs, in a GIS software package, which facilitated mapping in more detail than possible when limited to aerial photographs and stereoscope. Two land system boundaries were extensively modified, resulting in one land system being renamed and the other subdivided with some landforms being incorporated into other systems.

We grouped our land systems into existing soil-landscape zones (which describe physiography) where possible. Where we deemed existing physiographic mapping was inadequate (see discussion in Tille 2006), we newly identified and mapped new soil-landscape zones using the ‘bottom-up’ hierarchical approach of Schoknecht et al. (2004). We named zones based on those of Pain et al. (2011). We described zones using a combination of Pain et al. (2011), Tille (2006) and new information from this survey. Our new physiographic zones correlate to all prior mapping (see Table 4.2 in the Landscape evolution chapter).

The land system maps accompany this bulletin. Special purpose maps can be produced displaying any combination of information presented because the data have been captured in a multilayered georeferenced digital format. Not all the data collected during the field work are presented in this report or the accompanying map. More detailed information is available on request.

Landform diagrams

We identified representative areas from each land system, that displayed examples of the landforms within, to provide a basis for producing 3-dimensional (3D) perspective diagrams. We used ER Mapper software to display high-resolution aerial photograph imagery (supplied by Landgate at various dates) for each representative area, combined with a digital elevation model derived from the Shuttle Radar Topographic Mission (SRTM, supplied by Geoscience Australia 2010), to display as a 3D perspective diagram. The smoothed version of the digital elevation model gave the best results for creating the diagrams by reducing the amount of random noise associated with the SRTM in areas of low relief. The mapped land system boundaries were also draped over the aerial images. The ER Mapper software enabled the 3D diagrams to be orientated and tilted to obtain the optimum viewing position. We applied varying degrees of vertical exaggeration to help highlight particular landform attributes. When we were satisfied with the 3D diagram, we exported a high-resolution screen capture into Adobe Illustrator for enhancement and annotation. Where the 3D images were considered to be of inadequate quality to emphasise landform features, we selected 2-dimensional images supplied by Landgate or Google Earth.

References

Addison J (2012) ‘Rangeland condition monitoring – plants of the southern rangelands’, *Rangelands Memo*, 2(1):12–14.

Beard JS (1975) ‘The vegetation of the Nullarbor area, Explanatory Notes to Sheet 4’, *Vegetation survey of Western Australia, 1:1,000,000 vegetation series*, University of Western Australia Press.

Beard JS (1976) ‘The vegetation of the Boorabbin and Lake Johnston areas: map and explanatory memoir’, 2nd edn, *Vegetation survey of Western Australia, 1:250,000 vegetation series,* Vegmap Publications, Perth, Western Australia.

Beard JS (1981) 'The vegetation of the Swan area, Explanatory Notes to Sheet 7', *Vegetation survey of Western Australia, 1:1,000,000 vegetation series*, University of Western Australia Press.

Blight DF, Chin RJ and Smith RA (1984) 'Bencubbin, Western Australia: sheet SH 50–11 international index', *1:250,000 geological series – explanatory notes*, Geological Survey of Western Australia, Perth.

Bunting JA and van de Graaff WJE (1977) 'Cundeelee, Western Australia: sheet SH 51–11 international index', *1:250,000 geological series – explanatory notes*, Geological Survey of Western Australia, Perth.

Burnside D, Holm A, Payne A and Wilson G (1995) *Reading the rangeland. A guide to the arid shrublands of Western Australia*, Department of Agriculture, Western Australian Government.

Burvill GH (1988) 'The soils of the Salmon Gums District, Western Australia', *Technical bulletin 77*, Department of Agriculture, Western Australian Government.

Chin RJ, Hickman AH and Thom R (1984) 'Hyden, Western Australia: sheet SI 50–4 international index', *1:250,000 geological series – explanatory notes*, Geological Survey of Western Australia, Perth.

Chin RJ and Smith RA (1983) 'Jackson, Western Australia: sheet SH 50–12 international index', *1:250,000 geological series – explanatory notes*, Geological Survey of Western Australia, Perth.

Christian CS and Stewart GA (1953) 'General report on survey of Katherine–Darwin Region, 1946'. *Land research series no. 1*, Commonwealth Scientific and Industrial Research Organisation, Australia.

Curry PJ, Payne AL, Leighton KA, Hennig P and Blood DA (1994) 'An inventory and condition survey of the Murchison River catchment, Western Australia', *Technical bulletin 84*, Department of Agriculture, Western Australian Government.

Curry PJ, Payne AL and Wilcox DG (1983) 'Suggested descriptive terms for classes of foliar cover in arid zone shrublands', *Range Management Newsletter*, 83(3):12–13.

Dell J, How RA, Newbey KR and Hnatiuk RJ (1985) *The biological survey of the eastern Goldfields of Western Australia Part 3. Jackson–Kalgoorlie study area*, Records of the Western Australian Museum supplement number 23, Western Australian Museum, Perth.

Doepel JJG (1973) 'Norseman, Western Australia: sheet SI 51–2, international index', *1:250,000 geological series – explanatory notes*, Geological Survey of Western Australia, Perth.

Doepel JJG and Lowry DC (1970a) 'Balladonia, Western Australia: sheet SI 51–3 international index', *1:250,000 geological series – explanatory notes*, Geological Survey of Western Australia, Perth.

Doepel JJG and Lowry DC (1970b) 'Zanthus, Western Australia: sheet SH 51–15, international index', *1:250,000 geological series – explanatory notes*, Geological Survey of Western Australia, Perth.

Fletcher WJ (1991) *Impact and production of feral goats in an arid mulga shrubland*, MSc thesis, University of Western Australia.

Fletcher WJ (1995) 'Yerilla goat grazing study, 1989–1990 – a summary of results, findings and observations', *Miscellaneous publication 20/95,* Department of Agriculture, Western Australia.

Galloway P, van Gool D, Griffin T, Stuart-Street A, Pathan S and Laycock J (in press) 'Western Australian Soil Groups: a key to classify soils', *Resource management technical report 427*, Department of Primary Industries and Regional Development, Western Australian Government.

Gee RD (1982) ‘Southern Cross, Western Australia: sheet SH 50–16 international index’, *1:250,000 geological series – explanatory notes*, Geological Survey of Western Australia, Perth.

Gower CF and Bunting JA (1976) ‘Lake Johnston, Western Australia: sheet SI 51–1 international index’, *1:250,000 geological series – explanatory notes*, Geological Survey of Western Australia, Perth.

Grealish GJ and Wagnon JR (1995) ‘Land resources of the Bencubbin area’, *Land resources series 12*, Department of Agriculture, Western Australian Government.

Griffin TJ (1989) ‘Widgiemooltha, Western Australia: sheet SH 51–14 international index’, 2nd edn, *1:250,000 geological series – explanatory notes*, Geological Survey of Western Australia, Perth.

Hacker RB (1988) *The Western Australian Rangeland Monitoring System for arid shrublands instruction manual, Part 1: Field operations*, version 3, Department of Agriculture, Western Australian Government.

Hall NJ and Keighery GJ (1993) *The biological survey of the eastern Goldfields of Western Australia, Part 9: Norseman–Balladonia study area*, Records of the Western Australian Museum supplement number 42, Perth.

Holm A, Freidel F, Burnside D, Duffecy J, Fitzgerald D and Brennan G (2002) ‘Rangeways: Community-based planning for ecologically sustainable land use in the Western Australian Goldfields’, *Miscellaneous publication 9/2002*, Department of Agriculture, Western Australian Government.

How RA, Newbey KR, Dell J, Muir BG and Hnatiuk RJ (1988) *The biological survey of the eastern Goldfields of Western Australia Part 4. Lake Johnston – Hyden study area*, Records of the Western Australian Museum supplement number 30, Western Australian Museum, Perth.

Hunter WM (1991) ‘Boorabbin, Western Australia: sheet SH 51–13 international index’, 2nd edn, *1:250,000 geological series – explanatory notes*, Geological Survey of Western Australia, Perth.

Isbell RF (2016) *The Australian Soil Classification*, 2nd edn, CSIRO Publishing, Collingwood, Australia.

Keighery GJ and Hall NJ (1992) *The biological survey of the eastern Goldfields of Western Australia, Part 8: Kurnalpi–Kalgoorlie study area,* Records of the Western Australian Museum supplement number 41, Western Australian Museum, Perth.

Keighery GJ, McKenzie NL and Hall NJ (1995) *The biological survey of the eastern Goldfields of Western Australia, Part 11: Boorabbin – Southern Cross study area, and Part 12: Barlee–Menzies study area*, Records of the Western Australian Museum supplement number 49, Western Australian Museum, Perth.

Mabbutt JA, Litchfield WH, Speck NH, Sofoulis J, Wilcox DG, Arnold JA, Brookfield M and Wright RL (1963) ‘General report on the lands of the Wiluna–Meekatharra area, Western Australia, 1958’. *Land research series no. 7*, Commonwealth Scientific and Industrial Research Organisation, Australia.

Mitchell AA and Wilcox DG (1994) *Arid shrubland plants of Western Australia*, revised edition, University of Western Australia Press, Perth.

Moore G (1998) 'Soil salinity', in Moore G (ed) 'Soil guide: A handbook for understanding and managing agricultural soils', *Bulletin 4343*, Agriculture Western Australia, Western Australian Government.

Munsell Color Company (2009) *Munsell soil color chart*, 2009 revision, Munsell Color Company Inc., Baltimore, Maryland, USA.

NCST (National Committee on Soil and Terrain) (2009) *Australian soil and land survey field handbook*, 3rd edn, CSIRO Publishing, Melbourne.

Newbey KR, Dell J, How RA and Hnatiuk RJ (1984) *The biological survey of the eastern Goldfields of Western Australia, Parts 1 and 2*, Records of the Western Australian Museum supplement number 18, Western Australian Museum, Perth.

Nicholas B (1995) 'Ravensthorpe, Esperance and Salmon Gums Area land resources survey' (unpublished raw data) in Department of Primary Industries and Regional Development *Map unit database*, DPIRD, Western Australian Government, accessed 17 February 2021.

Northcote KH, with Beckmann GG, Bettenay E, Churchward HM, Van Dijk DC, Dimmock GM, Hubble GD, Isbell RF, McArthur WM, Murtha GG, Nicholls KD, Paton TR, Thompson CH, Webb AA and Wright MJ (1960–68) *Atlas of Australian soils*, Sheets 1 to 10 with explanatory data, CSIRO and Melbourne University Press, Melbourne.

Overheu T (1992) 'Condingup land system survey' (unpublished raw data) in Department of Primary Industries and Regional Development *Map unit database*, DPIRD, Western Australian Government, accessed 17 February 2021.

Overheu T (1995) 'Jerramungup land resources survey' (unpublished raw data) in Department of Primary Industries and Regional Development *Map unit database*, DPIRD, Western Australian Government, accessed 17 February 2021.

Overheu TD, Muller PG, Gee ST and Moore GA (1993) 'Esperance land resource survey', *Land Resources Series 8*, Department of Agriculture, Western Australian Government.

Pain C, Gregory L, Wilson P and McKenzie N (2011) 'The physiographic regions of Australia', *Explanatory notes*, Australian Collaborative Land Evaluation Program and National Committee on Soil and Terrain.

Payne AL, Mitchell AA and Hennig P (1998a) 'Land systems of the Kambalda area and surrounds', Private report prepared for WMC Resources Ltd. Natural Resource Management Services, Department of Agriculture, Western Australian Government.

Payne AL, Van Vreeswyk AME, Pringle HJR, Leighton KA and Hennig P (1998b) 'An inventory and condition survey of the Sandstone-Yalgoo-Paynes Find area, Western Australia', *Technical bulletin 90*, Department of Agriculture, Western Australian Government.

Pringle HJR (1995) 'Environmental considerations for the proposed Goldfields gas pipeline route through Wanjarri Nature Reserve', *Resource management technical report 148*, Department of Agriculture, Western Australian Government.

Pringle HJR, Van Vreeswyk AME and Gilligan SA (1994) 'An inventory and condition survey of the north-eastern Goldfields, Western Australia', *Technical bulletin 87*, Department of Agriculture, Western Australian Government.

Rangelands NRM (2015) *Field guide to common grasses of the southern rangelands*, Rangelands NRM, Perth, Western Australia.

Raupach M and Tucker BM (1959) 'The field determination of soil reaction', *Journal of the Australian Institute of Agricultural Science*, 25:129–33.

Rayment GE and Higginson FR (1992) 'Australian laboratory handbook of soil and water chemical methods', *Australian soil and land survey handbook*, Inkata Press.

Russell P and Fletcher W (2003) ‘Relative palatability of selected perennial plants in the southern rangelands of Western Australia: Results of survey of rangeland practitioners’, *Range Management Newsletter,* 3:1–18.

Schoknecht NR, Tille PJ and Purdie BR (2004) ‘Soil-landscape mapping in south-Western Australia: an overview of methodology and outputs’, *Resource management technical report 280*, Department of Agriculture, Western Australian Government.

Scholz GGH (1990) ‘Soil morphology and chemistry of the Cascades area, Western Australia’ (unpublished raw data) in Department of Primary Industries and Regional Development *Map unit database*, DPIRD, Western Australian Government, accessed 17 February 2021.

Scholz GGH and Smolinski HJ (1996) ‘Soils of the Mount Beaumont area’, *Land resources series 7*, Department of Agriculture, Western Australian Government.

Speck NH, Bradley J, Lazarides M, Patterson RA, Slayter RO, Stewart GA and Twidale CR (1960) ‘The lands and pastoral resources of the North Kimberley area, Western Australia’, *Land research series 4*, Commonwealth Scientific and Industrial Research Organisation, Australia.

Speck NH, Wright RL, Rutherford GF, Fitzgerald K, Thomas F, Arnold JA, Basinski JJ, Fitzpatrick EA, Lazarides M and Perry RA (1964) ‘General report on the lands of the West Kimberley area, Western Australia’, *Land research series 9*, Commonwealth Scientific and Industrial Research Organisation, Australia.

Stewart GA, Perry RA, Paterson SJ, Traves DM, Wright RL, Slayter RO, Dunn PR, Jones PJ and Sleeman JR (1970) ‘Lands of the Ord–Victoria area, Western Australia and Northern Territory’, *Land research series 28*, Commonwealth Scientific and Industrial Research Organisation, Australia.

Stuart-Street A, Short N, Galloway P and Schoknecht N (2020) ‘A simple guide for describing soils’, Department of Primary Industries and Regional Development, Western Australian Government.

Tille P (2006) ‘Soil-landscapes of Western Australia’s rangelands and arid interior’, *Resource management technical report 313*, Department of Agriculture and Food, Western Australian Government.

Tinley KT and Pringle H (2014) *Rangeland rehydration 2: manual*, Rangelands NRM and Durack Institute of Technology.

van Gool D, Tille P and Moore GA (2005) ‘Land Evaluation Standards for Land Resource Mapping’, 3rd edn, *Resource management technical report 298*, Department of Agriculture and Food, Western Australian Government.

Verboom WH, Griffin EA and Frahmand M (2004) ‘Southern Cross-Hyden land resources survey’ (unpublished raw data) in Department of Primary Industries and Regional Development *Map unit database*, DPIRD, Western Australian Government, accessed 17 February 2021.

Waddell PA, Gardner AK and Hennig P (2010) ‘An inventory and condition survey of the Western Australian part of the Nullarbor region’, *Technical bulletin 97*, Department of Agriculture and Food, Western Australian Government.

Williams IR (1973) ‘Kurnalpi, Western Australia: sheet SH 51–10 international index’, *1:250,000 geological series – explanatory notes*, Geological Survey of Western Australia, Perth.

Wyche S (1998) ‘Kalgoorlie, Western Australia: sheet SH 51–9 international index’, 2nd edn, *1:250,000 geological series – explanatory notes*, Geological Survey of Western Australia, Perth.

3 Climate

PA Waddell and PD Galloway

Introduction

Over millions of years, the climate of the southern Goldfields has changed from humid, warm to cool temperate with periods of freezing conditions to its current dry temperate to arid climate. In this chapter, we summarise current knowledge of the paleoclimate of southern Australia, WA and the survey area. We then describe, for the survey area, the climatic and bioclimatic zones, and the modern climatic drivers and patterns, including rainfall and temperature, based on climate data from the last hundred years.

Paleoclimate

An understanding of paleoclimates helps context the evolving landscape because climate affects vegetation, weathering, deposition and erosion. Further, paleovegetation limits the evolutionary possibilities to the present. Finally, past and present vegetation assemblages affect soil biota and the distribution and presence of secondary minerals.

Paleontological studies provide evidence of past climates but have inherent uncertainty in ascribing prevailing conditions at the time the fossils were living. Paleoclimate interpretations are often qualitative because they are gained from scarce and incomplete information within spatially and temporally discontinuous geology and fossil records. Sedimentary successions preserve attributes of sedimentary facies specific to the climate at the time of deposition, but evidence from fossils is often biased in both taxa type and preservation probability towards moist environments. Cool and dry paleoclimates preserve less paleontological evidence in the sedimentary record because less sedimentation occurs, stratigraphic discontinuity occurs more often, and the geographic extent of the sedimentary record becomes more fragmentary. Therefore, rainforest taxa are more often preserved than arid zone taxa. Further, pollen data has inherent uncertainties relating to varying pollen production rates and modes of dispersal between co-habiting taxa. These uncertainties introduce ambiguity in interpreting whether paleopollen (palynology) abundance relates to the proximity of taxa to the location or their dominance. Despite these challenges, sedimentology, stable isotope, radioisotope, paleontology and palynology studies continue to refine our knowledge of the paleoclimate and paleovegetation.

Australia preserves a history of paleoclimate variability resulting from its tectonic quiescence and absence of glaciation after the Permian. Tectonics and the global arrangement of continents is the primary driver of long-term climate (10^7 to 10^8 years) because they control the distribution of ocean currents that transfer heat energy. At shorter timescales, climate changes result from variation in solar energy inputs driven by astronomic planetary motion and sun cycles, and the combined interaction of the biosphere, atmosphere, hydrosphere and lithosphere assimilating carbon dioxide in their respective cycles (e.g. biogenic carbon sources stored in sedimentary deposits and carbon dioxide assimilated in weathering products of rocks).

Over the Cenozoic Era, the survey area has been moving north, from near-polar latitudes (65–60 degrees south) towards its current mid-latitude position. Over the same period, the globe has transitioned from greenhouse to icehouse conditions. This general transition was driven by the development of the Antarctic circumpolar current initiated when the Australo-Antarctic Gulf opened to form the Southern Ocean about 43 million years ago (43 Ma) as described by Hou et al. (2008) and McGowran and Hill (2015). Paleoclimate evidence from the survey area and nearby is consistent with this climate transition. Local paleoclimate has also been affected by marine transgressions that were influenced by tectonic motions.

Paleocene

The Early Paleocene climate is poorly resolved for Australia because the palynological evidence is sparse and conflicting (Benbow et al. 1995). A well-resolved record of terrestrial and marine paleontological evidence presented by Bowman et al. (2014) described the paleoclimate and paleovegetation of the Antarctic peninsula at a latitude of 65 degrees south over the period from the Cretaceous–Paleogene boundary into the Paleocene. This record is from Gondwana and covers the period when that study and southern WA lay at similar latitude, so it provides a reasonable proxy for paleoclimate and paleovegetation. The eastern Antarctic peninsula is envisaged by Bowman et al. (2014) as having a coastal lowland of warm to cool temperate rainforest, composed mainly of *Nothofagus*–podocarp–Proteaceae canopy, drained by rivers and wetlands that were bordered by coniferous rainforest. The uplands between valleys were drier and hosted open forest with diverse proteaceous shrubs and small trees. Subalpine and alpine areas were cooler and may have experienced freezing conditions – snow and ice – during winter, perhaps retaining some icecaps. Moisture availability was the most important ecological factor affecting vegetation. This varied ecosystem retained elements of warm- and cool-loving plants, and those capable of surviving freezing conditions. It also retained species that coped with a range of moisture regimes. Both features rendered the terrestrial ecosystems capable of responding to the relatively rapid climate changes that occurred either side of the Cretaceous–Paleogene extinction.

Australian evidence suggests the north-western WA coast was warm temperate with areas of developing aridity and seasonality, and wetter in the south (Martin 2006). Limited palynological evidence suggests southern Australia had a cool temperate rainforest with some taxa of tropical aspect (Benbow et al. 1995). The southern coastline was cool and wet, dominated by coniferous rainforest and relics from the preceding Cretaceous period with an understorey of ferns and mosses, and diverse proteaceous progenitors (Benbow et al. 1995; McGowran and Hill 2015; Peyrot et al. 2019), suggesting a similar situation to that described by Bowman et al. (2014).

Eocene

From the Early Eocene climatic optimum (about 50 Ma; McGowran and Hill 2015) to the Late Eocene (34 Ma), the survey area migrated from a latitude of about 60 degrees south to 50 degrees south. During this time, the northern shoreline of the Australo-Antarctic Gulf migrated with successive marine transgression–regression sequences, at times inundating the south of the survey area to about Norseman. Elevation of the landmass was like the present, so orographic effects were minimal and the climate gradient from maritime to continental interior was likely to be similar.

During the Early Eocene climatic optimum, warm temperate to tropical conditions prevailed along the western margin of Australia (Martin 2006 and references therein), extending eastwards along the north (Australian) and south (Antarctic) shorelines of the widening Australo-Antarctic Gulf (McGowran and Hill 2015 and references therein). The Australian hinterland experienced temperate rainforest characterised by *Nothofagus* spp. (southern beech; McGowran and Hill 2015).

In the Early Eocene after the climatic optimum, southern regions became cooler and wetter, while north-west WA gradually warmed and aridity continued. The southern Australian coastline had a wet, cool temperate climate and was vegetated by coniferous lowland rainforest with a significant proteaceous element (Benbow et al. 1995). In central Australia, the vegetation was predominantly Cunoniaceae and Myrtaceae forests, and Casuarinaceae and *Nothofagus* were rare, suggesting dry seasons (Martin 2006).

Despite fluctuating sea-surface temperatures, there was a general cooling trend through the Middle–Late Eocene, though humidity remained high (Martin 2006). Cool temperate rainforests became more widespread, and conifers and *Nothofagus* increased in prominence with a concordant decline in tropical taxa (Benbow et al. 1995; McGowran and Hill 2015). The interior was temperate and seasonally dry, with forests that contained Proteaceae, Myrtaceae and casuarinas (Hopper and Gioia 2004; Martin 2006). Rare rainforest associates were restricted to the wetter valley floors (Truswell and Harris 1982; Benbow et al. 1995; McGowran and Hill 2015). *Nothofagus* fossils, indicating a temperate hinterland, are present in Middle–Late Eocene sediment cores from Coolgardie (Truswell and Harris 1982), Lake Lefroy (Itzstein-Davey 2003), Mulga Rocks (Mack and Milne 2015) and Zanthus (Milne 1988), all in the southern Goldfields region. The *Nothofagus*-dominated forests of eastern Australia were not as prominent in WA. Instead, WA had a more diverse and variable vegetation that displayed features suggesting seasonal dryness, aridity and nutrient scarcity (Mack 2016). Proteaceae were prominent at Lake Lefroy (Itzstein-Davey 2003) and further inland at Mulga Rocks (Mack and Milne 2015) and Zanthus (Milne 1988). These proteaceous fossils possessed scleromorphic features that evolved to cope with nutrient scarcity (Hill 1998; Mack 2016). Some Late Eocene Proteaceae also evolved xeromorphic features, which conserve water and indicate seasonally dry conditions, from scleromorphic adaptations. Such evidence is present in fossils from Kojonup, Calingiri and Walebing, west of the southern Goldfields (Mack 2016).

Scleromorphic features of fossils suggest nutrient depletion, which imply deeply weathered regolith. This evidence is reinforced by sediments rich in kaolin and smectite clays, which also indicate chemical weathering. Deep weathering of the regolith occurred in moderate or cooler climates, as supported by both the fossil record, previously described, and by the $\delta^{18}O$ isotope value of clays (Chivas and Bird 1995). Subdued relief preserved extensive weathered regolith.

Biochemical weathering of regolith was enhanced by root exudates of the dominant proteaceous vegetation in synchrony with bacterial exudation described by Fritz and Yapp (2018) and facilitated bacterial formation of iron-rich secondary minerals in soil profiles (Pate et al. 2001; Lambers et al. 2009). Organic exudates enhance clay weathering and dissolution of silica from clay (Ochs 1996), thus increasing silica concentration in groundwaters, surface waters and near-shore marine environments. Marine sponges sequestered the dissolved silica, forming extensive biosiliceous deposits across southern Australia in the Bremer and Eucla basins (Jones 1990; Gammon et al. 2000; Gammon and James 2003), including the Princess Royal spongolite in the survey area and Pallinup siltstone to the south. Gammon and James (2003) suggested the biosedimentary deposits record a Late Eocene marine environment of cool open-ocean waters and sheltered warm water near coasts. Recognising biologically mediated weathering processes resolves difficulties with supposed tropical deep (chemical) weathering in an environment so far south, whose fossil record indicates seasonality and humid cool to warm, temperate climates.

Oligocene

Significant global cooling occurred at the Eocene–Oligocene boundary (34 Ma). It is attributed to establishment of the Antarctic circumpolar current, which formed after the widening Australo-Antarctic Gulf was breached, giving birth to the Southern Ocean. The resultant current throughflow isolated Antarctica and increased the polar climate gradient, which decreased the temperature of the Southern Ocean. Antarctica subsequently became completely glaciated. Cooling of south-west WA was subdued compared to south-east Australia and much of the world because the WA climate was buffered by the developing proto-Leeuwin current and warm water gyres within the Great Australian Bight (Macphail 2007; McGowran and Hill 2015). This relative climate stability of south-western WA resulted in preservation of a diverse Oligocene terrestrial biosphere, which set the stage for pulses of further diversification and establishment of the Southwest Australia biodiversity hotspot (Nge et al. 2020).

Miocene

Across Australia including present arid zones, sediments and fossils indicate the Early to Middle Miocene was warm, wet and climatically stable. Lakes Lefroy and Cowan preserve Early to Middle Miocene Revenge Formation deposits. These are highly oxidised red clay, and coarse red sand and oolitic ironstone, deposited in freshwater fluvio-lacustrine conditions with seasonal dryness (Clarke 1994; Zheng et al. 1998). The deposits suggest a lowland wetland because they retain pollen indicating rainforest (Zheng et al. 1998). The lakes lay in paleovalleys close to the Miocene Southern Ocean shoreline (Hou et al. 2008), so the surrounding landscapes were influenced by the maritime climate that increased local precipitation and weathering rates. While rainforest assemblages remained widespread, sedimentary deposits in inland areas show increased abundance and diversity in pollen of Myrtaceae, Poaceae, acacia and Asteraceae, indicating seasonal rainfall (Hopper and Gioia 2004). In southern Australia conifers started to diminish (McGowran and Hill 2015). The Miocene climatic optimum concluded about 15 Ma (McGowran and Hill 2015), and the climate has been cooling and drying since.

During the Middle to Late Miocene, the Antarctic ice sheet expanded significantly becoming similar to the present (Haywood et al. 2009). This influenced atmospheric circulation, resulting in cool, dry conditions and aridity inland away from WA Miocene coastlines. The onset of aridity in the Late Miocene, after the warm, wet Miocene climatic optimum, was marked by the cessation of major inland drainage systems in WA (Martin 2006; Byrne et al. 2008). Drying also changed the weathering and sedimentation regime from chemical to predominantly physical; erosion rates increased as vegetation cover reduced, as indicated by the widespread deposition of fluviatile, coarse gravels (Byrne et al. 2008 and references therein) and increasing illite and chlorite clays in marine deposits (McGowran and Hill 2015).

The Late Miocene climate was cold and dry which resulted in significant contraction of rainforest and expansion of eucalypt and casuarinaceous sclerophyll vegetation. With the cold, drying climate and onset of desiccation, arid-adapted taxa began to diverge. The extent and diversity of rainforest and temperate vegetation decreased, replaced by diverse Neogene vegetation with a tolerance and/or adaptability to dryness, impoverished soils and fire. This facilitated the differentiation and expansion of eucalypts (Truswell and Harris 1982; McGowran and Hill 2015) and speciation within the arid zone (Byrne et al. 2008).

The Miocene–Pliocene paleovegetation record for the WA arid zone is limited and correlations with other southern Australian records are tenuous because of evolutionary divergence at the Eocene–Oligocene boundary (Nge et al. 2020). Paleovegetation identified from arid areas of southern Australia at comparable latitude indicate vegetation assemblages that tolerate dryness (Lange 1978; Truswell and Harris 1982 and references therein).

Pliocene

The seasonal temperate climate continued into the Pliocene, fluctuating with periods of extended aridity (Dodson and Macphail 2004). Early Pliocene aridity succumbed to a warm and humid phase after 5 Ma when the vegetation assemblage of the Nullarbor transitioned from an arid phase of sparse woodland or shrubland to a humid environment with substantial summer rain that supported mesic eucalypt forests with banksia elements (Sniderman et al. 2016). This warm and humid phase resulted in widespread lacustrine environs across the south and south-west. Pluvial conditions within the survey area are indicated by freshwater clay deposits in Lake

Lefroy (Zheng et al. 1998) and the palynoflora of Lake Tay, which reveal a lake edge community of Casuarinaceae and eucalypt sclerophyll woodland with limited rainforest elements (Martin 2006 and references therein). A peak in moisture at 4.9 Ma, just after the Miocene–Pliocene transition, is inferred by concordant Myrtaceae and Cyperaceae pollen and fern spore peaks (Andrae et al. 2018), as well as pollen from rainforest associates from lacustrine environs in central South Australia.

This was followed by an abrupt change to cool, arid conditions which resulted in a significant expansion of C_4 plants in open woodland and grassland environs across Australia.[1] Prominent pollen from Amaranthaceae, Chenopodiaceae (chenopods) and Poaceae (grasses) indicates open vegetation communities, with trees from the Casuarinaceae, Cyperaceae and Proteaceae being locally abundant, and myrtaceous genera common (Truswell and Harris 1982; Martin 1998; Dodson and Macphail 2004). High charcoal content suggests conditions were dry enough to sustain wildfires (Dodson and Macphail 2004; Martin 2006). While grasslands were expanding in the hinterland, they were absent or poorly developed in south-west WA where more humid conditions persisted and leached sandy soils supported woody communities resembling Myrtaceae–Proteaceae scrub–heath (Dodson and Macphail 2004).

Similar shrubland and grassland assemblages are recorded off the north-west of WA – palynoflora indicate an increase in Asteraceae, Chenopodiaceae and Poaceae, and a decrease in the abundance of Casuarinaceae woodland (Martin 2006; Andrae et al. 2018). The increase in dominance of C_4 photosynthesis, as seen in the Chenopodiaceae and Poaceae, is attributed to increasing seasonality caused by a strengthening Australian northern monsoon, possibly associated with a more severe fire regime (Andrae et al. 2018). Evolutionary advantages of C_4 photosynthesis include drought resistance, salt tolerance, tolerance to high light levels and low carbon dioxide levels (Kadereit et al. 2012; Osbourne and Sack 2012; Zhou et al. 2018). The radiation of Chenopodiaceae and Poaceae indicates increasing aridity and salinity allied to further opening of the vegetation structure.

Palynology suggests that Pliocene and Pleistocene flora fluctuated in range and abundance with the climatic oscillations between arid and humid conditions linked to glacial and interglacial cycles (Dodson and Macphail 2004). Widespread speciation of sclerophyllous taxa across the south-west of WA may be associated with these climatic oscillations. Speciation was likely also enhanced by physical isolation caused by marine transgressions and geographic barriers (Hopper 1979; Hopper and Gioia 2004).

Pleistocene and Holocene

Within an oscillating pattern between global glacial and interglacial climates, the Pleistocene experienced further drying and transitioned to a fully arid climate (Zheng et al. 1998). With very limited glaciation on mainland Australia, the climate associated with glacial periods was colder and drier, with interglacial periods warmer and more humid. The Early to Middle Pleistocene alternated between open vegetation during drier periods and wooded vegetation in wetter periods (Martin 2006). Vegetation cover reduced during glacial periods, especially in arid regions, resulting in extensive areas becoming susceptible to erosion, increasing sand and dust mobility (Bowler 1976), and forming and reshaping extensive dunefields.

In south-west WA by the start of the Pleistocene, closed rainforest taxa such as *Nothofagus* and *Podocarpus* were extinct (Hopper and Gioia 2004), and sclerophyll woodland and forest became dominant. Pollen records in north-west WA indicate a continuing drying climate –

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[1] During photosynthesis, C_4 plants produce compounds with 4 carbon atoms, resulting in enhanced water and nitrogen efficiency. This facilitates tolerance to heat, high light intensity and moisture-limiting conditions. By comparison, C_3 plants photosynthesise molecules with 3 carbon atoms and they grow better in cool, moist conditions and at lower light intensities.

desert shrubs and grasslands were increasing while tree cover decreased (Martin 2006). Similarly, dry glacial cycles facilitated the expansion of grasslands and shrublands from the semi-arid and arid zone into much of southern Australia and the vegetation became dominated by Asteraceae, Poaceae and Chenopodiaceae (Dodson and Macphail 2004). Further south, wet eucalypt forests, present during interglacial periods, were replaced by mallee-eucalypt shrubland and open heath communities during dry glacial periods (Martin 2006 and references therein).

Zheng et al. (1998) dated the onset of fully arid conditions by the presence of the first gypsum deposits in Lake Lefroy at 500,000 years ago (500 Ka). Episodic extreme aridity occurred from 25 Ka and peaked at 18–16 Ka, with a peak in gypsum dune formation and mobility of sand dunes in inland deserts (Bowler 1976). The contraction of ancient river systems into networks of salt lakes increased the prominence of saline habitats and likely facilitated the radiation of the Chenopodiaceae into inland arid environments (Shepherd et al. 2004). Fluctuations between aridity and extreme aridity represent the modern climate of the survey area.

Lake bed and eolian deposits south and east of Lake Lefroy and Lake Cowan, in the centre and south of the survey, provide evidence of recent climate change – conditions more arid than at present were prevalent from 6,000 to 2,800 years ago (Zheng et al. 2002). Current conditions displaying slightly more humidity have been essentially stable for the past 2,800 years. This recent variability is associated with the fluctuating strength and size of the subtropical high-pressure ridge, which is described below.

Present climatic pattern

The present climate of southern WA and the southern Goldfields is significantly influenced by the subtropical high-pressure ridge, which encircles the globe in mid-latitudes. It results from the descent of cold, dry air generated by Hadley cells, which are vertical atmospheric circulation cells that transport heat energy from the tropics to the mid-latitudes. The subtropical ridge has a dominant effect on seasonal variability over the survey area – in summer it is located to the south and during winter it is located to the north.

The predominant climatic pattern during the warmer months (October–April) is influenced by high-pressure anticyclonic systems that form the subtropical ridge. These slow-moving systems generate warm and dry easterly winds that blow from the desert interior and result in clear skies and hot daytime weather. Heat troughs develop along the west coast when the easterly winds interact with moist and cool maritime air from the Indian Ocean. Heat troughs periodically affect the survey area when they interact with cold fronts to the south of the continent and move eastwards. The heat troughs cause heatwaves and can generate thunderstorms if sufficient moisture is present in air to the west of the migrating trough. Thunderstorm activity is occasionally enhanced by upper-level troughs feeding additional moisture from the north-west, which can generate widespread heavy rainfall.

Cyclones are intense low-pressure systems that form above tropical waters off the north-west coast. Remnants of tropical cyclones occasionally disrupt the predominant summer pattern when they move south and inland from the north-west, degenerating into rain-bearing depressions that result in heavy rainfall and localised flooding.

During the cooler months (May–September) the subtropical ridge moves north of the survey area and the predominant weather shifts to a winter pattern. During this period, low-pressure systems track from west to east across the south of the state, generating cold fronts bearing rain and moderate to severe westerly to southerly winds. Rain usually declines in intensity as the frontal system moves eastward, so the survey area tends to receive smaller amounts of rain more regularly during cooler months, compared to occasional heavy rain during the warm season. High-pressure systems that follow the fronts usually result in gentle breezes and clear skies, causing low minimum temperatures with occasional overnight frosts and warm days.

Climate zones

Based on latitude, Australia occurs within 2 broad climate zones: tropical and temperate. The survey area occurs within the south temperate zone, which extends from the Tropic of Capricorn (about 23.5° south latitude) to the Antarctic Circle (about 66.5° south latitude).

The popular Köppen climate classification system is based on what vegetation grows in each climatic region. It subdivides Australia into 3 main climate groups: tropical, dry and temperate. The survey area occurs within dry and temperate climates. Within all climate groups, subgroups are based on seasonal precipitation and temperature. Most of the west of the survey area occurs within a temperate Mediterranean climate, which is characterised by hot, dry summers and cool, wet winters. The north-east has a dry, desert climate characterised by high evaporation and low precipitation, typically defined by a mean annual rainfall of 250 mm or less.

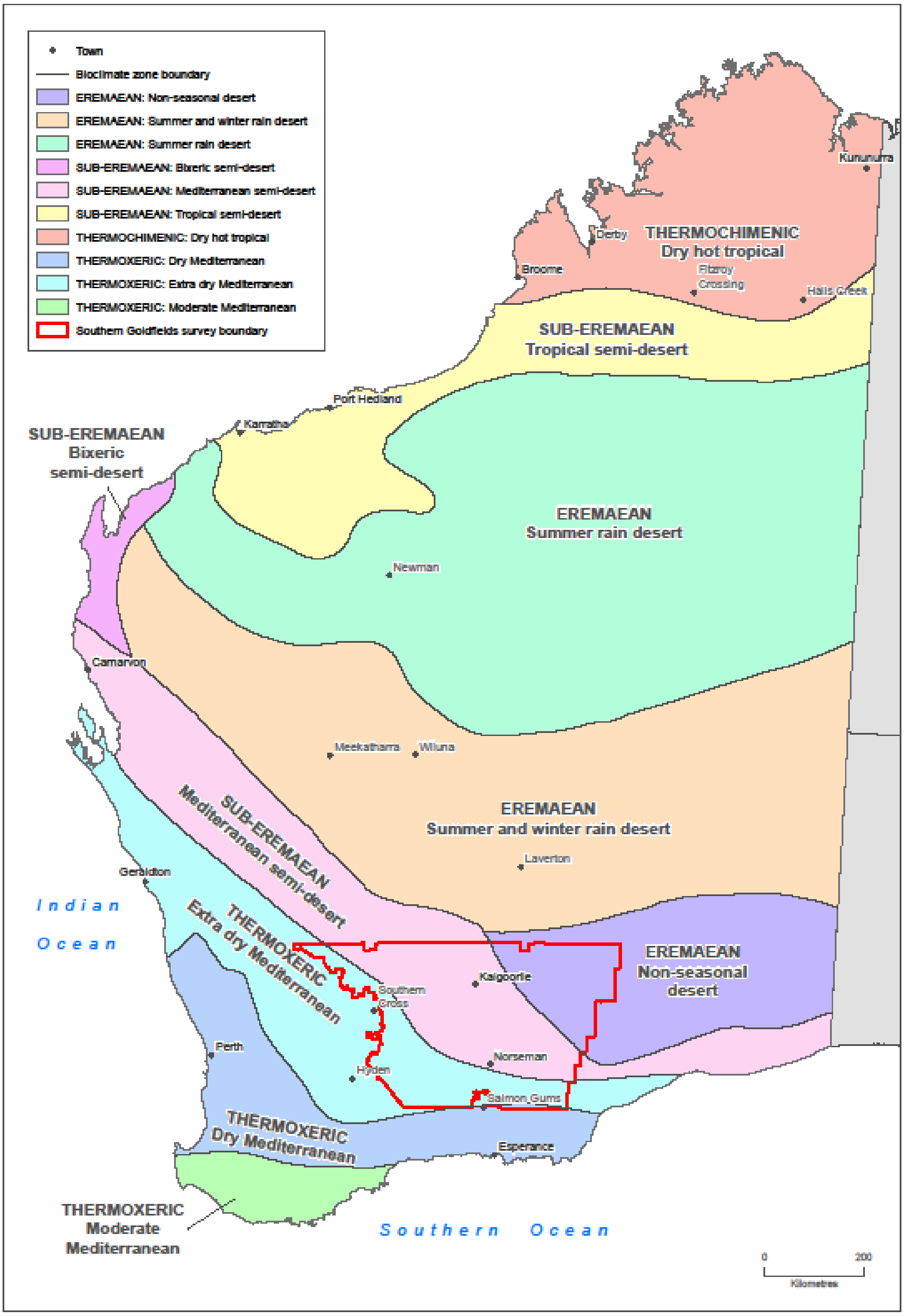
Though the Köppen system is highly regarded, we used bioclimatic zones defined by Beard (1990), which follow the climate classification system of Bagnouls and Gaussen (1957). Indices are based on the length of the dry season and fit better with major vegetation boundaries. Furthermore, the vegetation component of the Köppen system classifies much of the survey area within the grassland group (BoM 2021), which is useful and highly regarded for national scale assessments but fails to identify regional variation. We consider this nomenclature confusing for the survey area because most vegetation is woodland and shrubland.

Bioclimatic zones

Bioclimatic zones classify regions by climate characteristics that influence the distribution of organisms. The bioclimatic zones of WA were determined by major vegetation boundaries (Beard 1990) that correspond with major climatic zones based on the length of the dry season.

The survey area predominantly straddles 4 bioclimatic zones (Figure 3.1). The climate over the west, south-west and south is extra-dry Mediterranean (Thermoxeric). This zone is characterised by 7 to 8 dry months a year and typically experiences hot, dry summers and cold, wet winters. In the west, rainfall peaks around June and July, and the coolest months are July and August. Temperatures peak during the hot summer months (December to February; see map inset of Southern Cross in Figure 3.2). In the south-east, rainfall is more consistent because of proximity to the Southern Ocean. Rainfall peaks in winter around May and June before the coolest months of July and August, and there are lesser peaks in late spring (November) and late summer (February–March), most likely associated with thunderstorms or remnant tropical cyclones. Here also, temperatures peak during the hot summer months (December to February; see map inset of Balladonia in Figure 3.2).

The climate over the central portion is semidesert Mediterranean (Sub-Eremaean). The zone is characterised by 9 to 11 dry months a year. Summers are hot and dry, and winters, which deliver most of the rain, are short and cold. In the lower mid-centre of the survey area, on the southern margin of this climate zone, this description is supported by climate information from Norseman. Here, rainfall peaks in May and June, and the coolest months are June, July and August. Temperatures peak during the hot summer months (December to February; see map inset of Norseman in Figure 3.2). However, data from Kalgoorlie–Boulder indicates bimodal rainfall in the upper mid-centre of the survey area. Rainfall peaks in February and March, which coincides with the latter part of the hot period from November to March. Rainfall declines to a seasonal low in April and then increases over May to a winter peak in June that is less than the summer peak. This winter peak in rain declines over the coolest months of July and August, reaching its lowest in September (see map inset of Kalgoorlie–Boulder in Figure 3.2). This deviation in the Kalgoorlie–Boulder data from the typical characteristics of a semidesert Mediterranean climate is likely associated with recent (about 20 years) changes in seasonal rainfall patterns, where summer rainfall has gradually increased and winter rainfall has decreased (Figure 3.4).

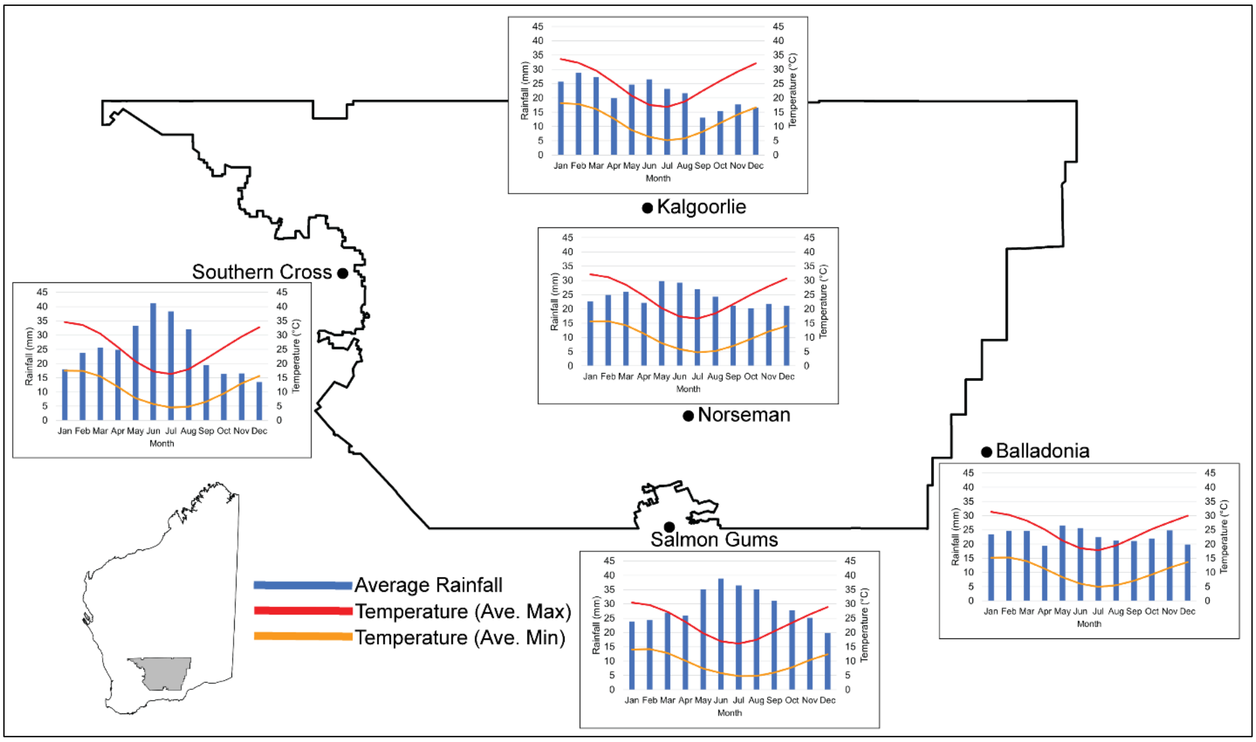


Note: Map is based on Beard's (1990) WA bioclimatic zones which follow the climate classification system of Bagnouls and Gaussen (1957).

Figure 3.1: Bioclimatic zones of Western Australia

The climate over the north-east is non-seasonal desert (Eremaean). This zone can experience 12 dry months a year, although because it is non-seasonal (or uniform), there is an equal chance of rain in any month.

The southernmost border of the survey area occurs along latitudes where the climate transitions into dry Mediterranean, which is characterised by 5 to 6 dry months. Rainfall tends to peak between May and August. Temperatures peak during the warm summer months (December to February; see map inset of Salmon Gums in Figure 3.2).



Source: SILO Patched Point Data (2021)

Figure 3.2: Average monthly temperature and rainfall across the survey area, 1920–2021

Rainfall

Rainfall patterns vary across the survey area according to regional differences defined by the 3 bioclimatic zones (Figure 3.1). The Sub-Eremaean and Eremaean zones of the north-east are influenced mostly by summer rainfall from north-west cloud bands, thunderstorms and tropical depressions. The Thermoxeric zone of the south-west is influenced mostly by winter rainfall from cold fronts associated with low-pressure systems. Occasionally, summer rainfall patterns affect areas further south and winter fronts extend to the north.

Climate change has resulted in the subtropical high-pressure ridge migrating southward in recent years (Hope et al. 2012). This is causing a drying trend across southern Australia (Stern and Dahni 2013) that also affects the timing and amount of rainfall across the survey area.

Most of the survey area has mean annual rainfall of 250–300 mm (Figure 3.3). Previously, rainfall was relatively uniform with subdued peaks in summer and winter and a dry period over spring; now, it is summer-dominant. The north and east have a mean annual rainfall of 150–250 mm that previously had no seasonal tendency but is now more likely over summer. The west and south have a mean annual rainfall range of 300–400 mm, which was previously winter-dominant but is now becoming more uniform throughout the year. Some population centres within or close to the survey area provide site-specific rainfall data (Table 3.1).

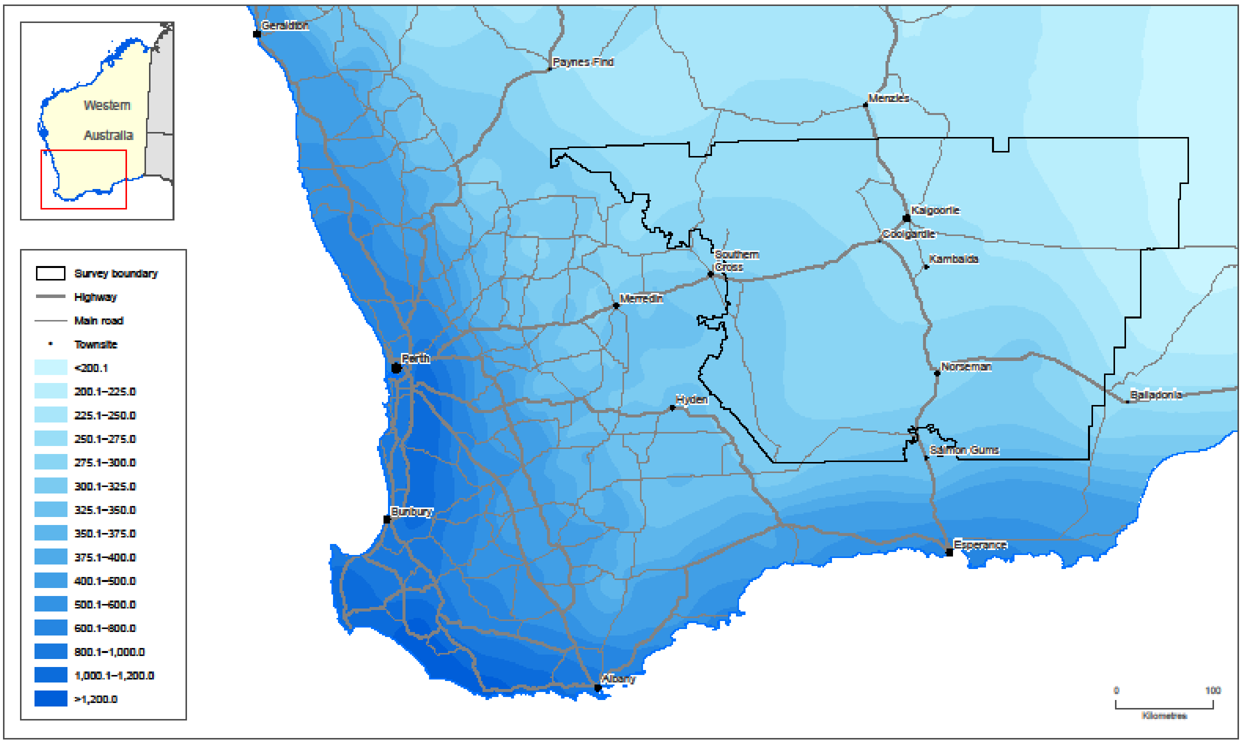


Figure 3.3: Mean annual rainfall isohyets across the survey area, 1910–2020

Table 3.1: Rainfall data for population centres within or close to the survey area

BoM station (number)	Location	Mean annual rainfall (mm)	Median annual rainfall (mm)	Recording period
Southern Cross (12320)	Just outside western survey boundary	301.3	303.6	1996–2021
Coolgardie (12018)	Central north of the survey area	269.6	263.5	1893–2020
Kalgoorlie–Boulder (12038)	Central north of the survey area	265.6	254.0	1939–2021
Norseman (12009)	Central south of survey area	286.8	256.2	1999–2021
Salmon Gums (12071)	Outside survey boundary near centre of southern margin	354.6	346.7	1932–2021
Balladonia (11017)	Just outside the south-east survey boundary	268.2	252.8	1891–1943, 1961–2021

BoM = Bureau of Meteorology

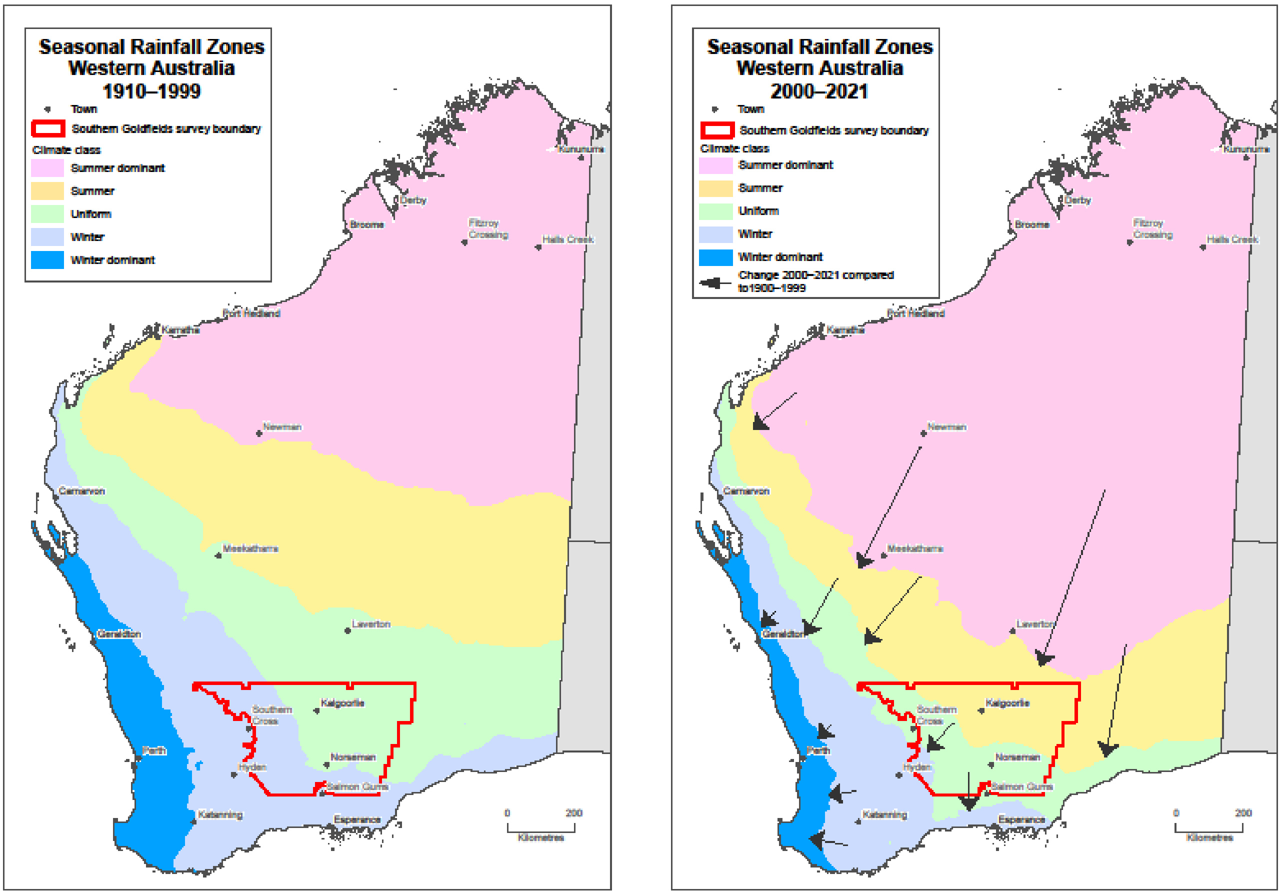
Source: BoM (2022)

Rainfall across the survey area is inherently variable. In the highest 10% of years (decile 9 rain) it ranges from about 35% to 45% more than the mean across the survey area, from about 390 mm at Balladonia and Kalgoorlie, about 410 mm at Southern Cross and Norseman, and 470 mm at Salmon Gums. In contrast, rainfall in the lowest 10% of years (decile 1 rain) ranges from just over half to about three-quarters of the mean rain, from 150 mm at Kalgoorlie to 245 mm at Salmon Gums. Rainfall can also vary significantly over a single year. For example:

- over 83 years of records, in 1948 Kalgoorlie recorded 308 mm of rain in February, its highest ever recorded for that month, and during the same year had no rain in May
- over 83 years of records, in 1961 Salmon Gums recorded 109 mm of rain in April, its highest ever recorded for that month, and during the same year had no rain in November
- over 111 years of records, in 2001 Balladonia recorded 199 mm of rain in February, its highest ever recorded for that month, and during the same year had no rain in April.

Changing seasonal rainfall since the turn of the 21st century (Stephens 2021) is shown in Figure 3.4. The ratio of summer to winter rainfall has increased since 2000 and isohyets (lines of equal annual rainfall) have shifted 100 to 500 km south. Declining winter rainfall shrinks the Mediterranean bioclimatic zone and its subdivisions to the south-west, while increasing summer rainfall expands the semidesert and desert bioclimatic zones southwards.

These changes to seasonal rainfall patterns and temperatures affect the length of the dry season upon which the bioclimatic zones are based. Consequently, it is likely that bioclimatic zone boundaries will need reassessment. These climatic changes will also likely influence habitat extent, diversity and possibly speciation, and there will be implications for land management as fire regimes, erosion rates, and pasture and water availability change.



Note: Map presented with permission from Dr D Stephens, Agrometeorology Australia, agromet.com.au/products.

Figure 3.4: Changes to Western Australia's seasonal rainfall zones

Temperature

There is slight variation across the survey area between mean maximum temperatures, and there is slight variation between mean minimum temperatures. Some of the main population centres within or close to the survey area provide site-specific temperature data (Figure 3.2, Table 3.2). The mean maximum temperature for summer is 33.8 °C at Southern Cross, 32.6 °C at Kalgoorlie–Boulder, 31.8 °C at Norseman, 30.7 °C at Balladonia and 29.8 °C at Salmon Gums (BoM 2022). The mean minimum temperature for winter is 4.1 °C at Southern Cross, 4.5 °C at Norseman, 5 °C at Salmon Gums, 5.3 °C at Balladonia and 5.7 °C at Kalgoorlie–Boulder (BoM 2022).

Temperatures above 40 °C have been recorded across the survey area for all months between October and April inclusive; the highest was 48 °C at Balladonia on 31 December 1972. Freezing temperatures are experienced occasionally from March to October; the lowest was −6.1 °C at Salmon Gums in August 1947.

Temperatures are expected to continue rising because of climate change and by mid-century (2040–2059), mean annual temperature is projected to further increase to 1.2 °C under a low-emission scenario and 2.0 °C under a high-emission scenario (CSIRO and Bureau of Meteorology 2021).

Table 3.2: Temperature data for population centres within or close to the survey area

BoM station (number)	Mean maximum temperature (°C)			Maximum summer mean (°C)	Highest daily maximum (°C)	Mean minimum temperature (°C)			Minimum winter mean (°C)	Lowest daily minimum (°C)	Recording period
	Dec	Jan	Feb			June	July	Aug			
Southern Cross (12320)	33.0	34.7	33.7	33.8	46.7 (Feb 2005)	4.6	3.7	3.9	4.1	–5.0 (Jun 2006)	1996–2021
Kalgoorlie–Boulder (12038)	32.1	33.6	32.1	32.6	46.5 (Jan 1990)	6.3	5.1	5.7	5.7	–3.4 (Jul 1969)	1939–2021
Norseman (12009)	31.3	32.6	31.5	31.8	46.5 (Jan 2019)	4.8	4.1	4.5	4.5	–6.0 (Jun 2010)	1999–2021
Salmon Gums (12071)	29.1	30.7	29.6	29.8	46.3 (Jan 2011)	5.7	4.7	4.7	5.0	–6.1 (Aug 1970)	1932–2021
Balladonia (11017)	30.2	31.3	30.5	30.7	48.0 (Dec 1972)	5.8	4.8	5.3	5.3	–3.5 (Jul 2005)	1965–2021

Aug = August; BoM = Bureau of Meteorology; Dec = December; Feb = February; Jan = January

Source: BoM (2022)

References

Andrae JW, McInerney FA, Polissar PJ, Sniderman JMK, Howard S, Hall PA and Phelps SR (2018) 'Initial expansion of C4 vegetation in Australia during the late Pliocene', *Geophysical Research Letters*, 45:1–10, doi.org/10.1029/2018GL077833.

Bagnouls F and Gaussen H (1957) 'Les climats biologique et leur classification', *Annales de Géographie*, 66:193–220, doi.org/10.3406/geo.1957.18273.

Beard JS (1990) *Plant life of Western Australia*, Kangaroo Press, Kenthurst, New South Wales.

Benbow MC, Alley NF, Callan RA and Greenwood DR (1995) 'Geological history and palaeoclimate', in Dexel JF and Preiss WV (eds) *The Geology of South Australia, the Phanerozoic*, vol. 2, Geological Survey of South Australia Bulletin 54, pp 208–217.

BoM (Bureau of Meteorology) (2021) *Climate classification maps*, BoM website, Australian Government, accessed 21 December 2021.

BoM (Bureau of Meteorology) (2022) *Climate data online: rainfall and temperature data*, BoM website, Australian Government, accessed 10 January 2022.

Bowler JM (1976) 'Aridity in Australia: age, origins and expression in aeolian landforms and sediments', *Earth Science Reviews*, 12:179–310.

Bowman VC, Francis JE, Askin RA, Riding JB and Swindles GT (2014) 'Latest Cretaceous – earliest Paleogene vegetation and climate change at the high southern latitudes: palynological evidence from Seymour Island, Antarctic Peninsula', *Palaeogeography, Palaeoclimatology, Palaeoecology*, 408:26–47.

Byrne M, Yeates DK, Joseph L, Kearney M, Bowler J, Williams MAJ, Cooper S, Donnellan SC, Keogh JS, Leys R, Melville J, Murphy DJ, Porch N and Wyrwoll KH (2008), 'Birth of a biome: insights into the assembly and maintenance of the Australian arid zone biota', *Molecular Ecology*, 17:4,398–4,417.

Chivas AR and Bird MI (1995) 'Palaeoclimate from Gondwanaland clays', in Churchman GJ, Fitzpatrick RW and Eggleton RA (eds) 'Clays: Controlling the environment', *Proceedings of the 10th International Clay Conference*, Adelaide, 1993, pp 333–338.

Clarke JDA (1994) 'Evolution of the Lefroy and Cowan palaeodrainage channels, Western Australia', *Australian Journal of Earth Sciences*, 41(1):55–68.

CSIRO and Bureau of Meteorology (2021) *Western Australia's changing climate,* Climate change in Australia website, accessed 11 October 2021.

Dodson JR and Macphail MK (2004) 'Palynological evidence for aridity events and vegetation change during the Middle Pliocene, a warm period in Southwestern Australia', *Global and Planetary Change*, 41:285–307.

Fritz TO and Yapp CJ (2018) 'Miocene weathering environments in Western Australia—Inferences from the abundance and $^{13}C/^{12}C$ of $Fe(CO_3)OH$ in CID goethite', *Geochimica et Cosmochimica Acta*, 227:186–210, doi.org/10.1016/j.gca.2018.02.023.

Gammon PR, James NP, Clarke JDA and Bone Y (2000) 'Sedimentology and lithostratigraphy of Upper Eocene sponge-rich sediments, southern Western Australia', *Australian Journal of Earth Sciences*, 47:1,087–1,103.

Gammon PR and James NP (2003) 'Paleoenvironmental controls on Upper Eocene biosiliceous neritic sediments, southern Australia', *Journal of Sedimentary Research*, 73(6):957–972.

Haywood AM, Smellie JL, Ashworth AC, Cantrill DJ, Florindo F, Hambrey MJ, Hill D, Hillenbrand C, Hunter SJ, Larter RD, Lear CH, Passchier S and van de Wal R (2009) 'Middle Miocene to Pliocene History of Antarctica and the Southern Ocean', in Florindo F and Siegert

M (eds) *Developments in Earth and Environmental Sciences, Vol 8, Antarctic Climate Evolution*, The Netherlands, pp 401–463.

Hill RS (1998) 'Fossil evidence for the onset of xeromorphy and scleromorphy in Australian Proteaceae', *Australian Systematic Botany*, 11:391–400.

Hope P, Keay K, Ganter CJ, Li Y, Charles S, Fu G, Phatak A and Palmer M (2012) 'Southwest Western Australia's changing climate', in Bates B, Frederiksen C and Wormworth J (eds) *Indian Ocean Climate Initiative (2012) Western Australia's weather and climate: A synthesis of Indian Ocean Climate Initiative stage 3 research*, CSIRO and Bureau of Meteorology, Australia, pp 36–64.

Hopper SD (1979) 'Biogeographical aspects of speciation in the south-west Australian flora', *Annual Review of Ecology and Systematics*, 10:399–422.

Hopper SD and Gioia PG (2004) 'The south-west Australian floristic region: evolution and conservation of a global hot spot of biodiversity', *Annual Review of Ecology, Evolution, and Systematics*, 35:623–650.

Hou B, Frakes LA, Sandiford M, Worrall L, Keeling J, Alley NF (2008) 'Cenozoic Eucla Basin and associated palaeovalleys, southern Australia – Climatic and tectonic influences on landscape evolution, sedimentation and heavy mineral accumulation', *Sedimentary Geology,* 203:112–130.

Itzstein-Davey F (2003) *Changes in the abundance and diversity of Proteaceae over the Cainozoic in south-western Australia* [PhD thesis], The University of Western Australia.

Jones BG (1990) 'Cretaceous and tertiary sedimentation on the western margin of the Eucla Basin' *Australian Journal of Earth Sciences*, 37:317–329.

Kadereit G, Ackerly D and Pirie MD (2012) 'A broader model for C_4 photosynthesis evolution in plants inferred from the goosefoot family (Chenopodiaceae s.s.)', *Proceedings of the Royal Society B*, 279:3,304–3,311.

Lambers H, Mougel C, Jaillard B and Hinsinger P (2009) 'Plant-microbe-soil interactions in the rhizosphere: an evolutionary perspective', *Plant Soil*, 321:83–115.

Lange RT (1978) 'Carpological evidence for fossil *Eucalyptus* and other *Leptospermeae* (Subfamily Leptospermoideae of Myrtaceae) from a tertiary deposit in the South Australian arid zone', *Australian Journal of Botany*, 26:221–233.

Mack CL (2016) *Palynology of the Narnoo palaeovalley, Western Australia, and its implications for the biostratigraphy and palaeovegetation of southern Australia* [PhD thesis], Curtin University.

Mack CL and Milne LA (2015) 'Eocene palynology of the Mulga Rocks deposits, southern Gunbarrel Basin, Western Australia', *Alcheringa: An Australasian Journal of Palaeontology*, 39(4):444–458, doi.org/10.1080/03115518.2015.1022090.

Martin HA (1998) 'Late Cretaceous–Cainozoic palynology of the Poonarunna No. 1 well, Central Australia', *Transactions of the Royal Society of South Australia*, 122(3):89–138.

Martin HA (2006) 'Cenozoic climatic changes and the development of the arid vegetation of Australia', *Journal of Arid Environments*, 66:533–563.

Macphail M (2007) *Australian palaeoclimates: Cretaceous to Tertiary – a review of palaeobotanical and related evidence to the year 2000*, CRC LEME Special Volume Open File Report 151, Bentley, Western Australia.

McGowran B and Hill RS (2015) 'Cenozoic climate shifts in Southern Australia', *Transactions of the Royal Society of South Australia*, 139(1):19–37.

Milne LA (1988) 'Palynology of a late Eocene lignitic sequence from the western margin of the Eucla Basin, Western Australia', *Memoirs of the Association of Australasian Palaeontologists,* 5:285–310.

Nge FJ, Biffin E, Theile KR and Waycott M (2020) 'Extinction pulse at Eocene – Oligocene boundary drives diversification dynamics of two Australian temperate floras', *Proceedings of the Royal Society B*, 287:20192546, doi.org/10.1098/rspb.2019.2546.

Ochs M (1996) 'Influence of humified and non-humified natural organic compounds on mineral dissolution' *Chemical Geology,* 132:119–124.

Osborne CP and Sack L (2012) 'Evolution of C_4 plants: a new hypothesis for an interaction of CO_2 and water relations mediated by plant hydraulics', *Philosophical Transactions of the Royal Society B*, 367:583–600, doi.org/10.1098/rstb.2011.0261.

Pate JS, Verboom WH and Galloway PD (2001) 'Co-occurrence of Proteaceae, laterite and related oligotrophic soils: coincidental associations or causative inter-relationships?' *Australian Journal of Botany,* 49:529–560.

Peyrot D, Playford G, Mantle DJ, Backhouse J, Milne LA, Carpenter RJ, Foster C, Mory AJ, McLoughlin S, Vitacca J, Scibiorski J, Mack CL and Bevan J (2019) 'The greening of Western Australian landscapes: the Phanerozoic plant record', *Journal of the Royal Society of Western Australia*, 102:52–82.

Shepherd KA, Waycott M and Calladine A (2004) 'Radiation of the Australian Salicornioideae (Chenopodiaceae) – based on evidence from nuclear and chloroplast DNA sequences', *American Journal of Botany*, 91:1387–1397.

Silo Patched Point Data (2021) *Daily climatic data – Patched point dataset and DPIRD weather stations*, Queensland Government Open Data Portal, data.qld.gov.au/dataset/silo-patched-point-data, accessed 30 September 2021.

Sniderman JMK, Woodhead JD, Hellstrom J, Jordan GJ, Drysdale RN, Tyler JJ, and Porch N (2016) 'Pliocene reversal of late Neogene aridification', *Proceedings of the National Academy of Sciences*, 113(8):1999–2004, doi.org/10.1073/pnas.1520188113.

Stephens D (2021) *Australian seasonal rainfall zone maps*, Agrometeorology Australia website, Agrometeorology Australia.

Stern H and Dahni RR (2013) 'The distribution of climate zones across Australia: identifying and explaining changes during the past century', American Meteorological Society website, *Proceedings of the 93rd American Meteorological Society Annual Meeting*, Paper no. 564.

Truswell EM and Harris WK (1982) 'The Cainozoic palaeobotanical record in arid Australia: fossil evidence for the origins of an arid-adapted flora', in Barker WR and Greenslade PJM (eds) *Evolution of the Flora and Fauna of Arid Australia*, Peacock Publications, South Australia, pp 67–76.

Zheng H, Wyrwoll K-H, Li Z-X and Powell C (1998) 'Onset of aridity in southern Western Australia: a preliminary palaeomagnetic appraisal', *Global and Planetary Change*, 18:175–187.

Zheng H, Powell C and Zhou H (2002) 'Eolian and lacustrine evidence of late Quaternary palaeoenvironmental changes in south-western Australia', *Global and Planetary Change*, 35:75–92.

Zhou H, Helliker BR, Huber M, Dicks A and Akcay E (2018) 'C_4 photosynthesis and climate through the lens of optimality', *Proceedings of the National Academy of Sciences USA*, 115(47):12,057–12,062, doi.org/10.1073/pnas.1718988115.

4 Landscape evolution

PD Galloway and PA Waddell

Introduction

This chapter describes the geological formations, tectonic processes and geomorphological characteristics of the southern Goldfields. All are interrelated and interacting. This is particularly evident when describing geological features and tectonic processes because the formation and emplacement of distinct rock suites is driven by tectonic processes. Within the Geology section, where the rocks and geological setting are described, description of tectonic processes is limited to those that are important to understand the environment of formation.

In contrast, the Late Mesozoic and Cenozoic tectonic processes (largely Australia's movements post-Gondwana) are more fully described, after describing the general geology, to better frame the physiographic development of the survey area. Also included are descriptions of faulting and resistance to weathering and erosion (see Geomorphology section) because they are important drivers of landscape formation and evolution.

Using the well-established concept of 'patterns and processes', the landscape is subdivided into regional-scale 'land zones', each with distinctive characteristics resulting from a combination of particular geological events and processes, and climate and soil formation (both described elsewhere in this bulletin). Essentially, each land zone is characterised by particular landform patterns.

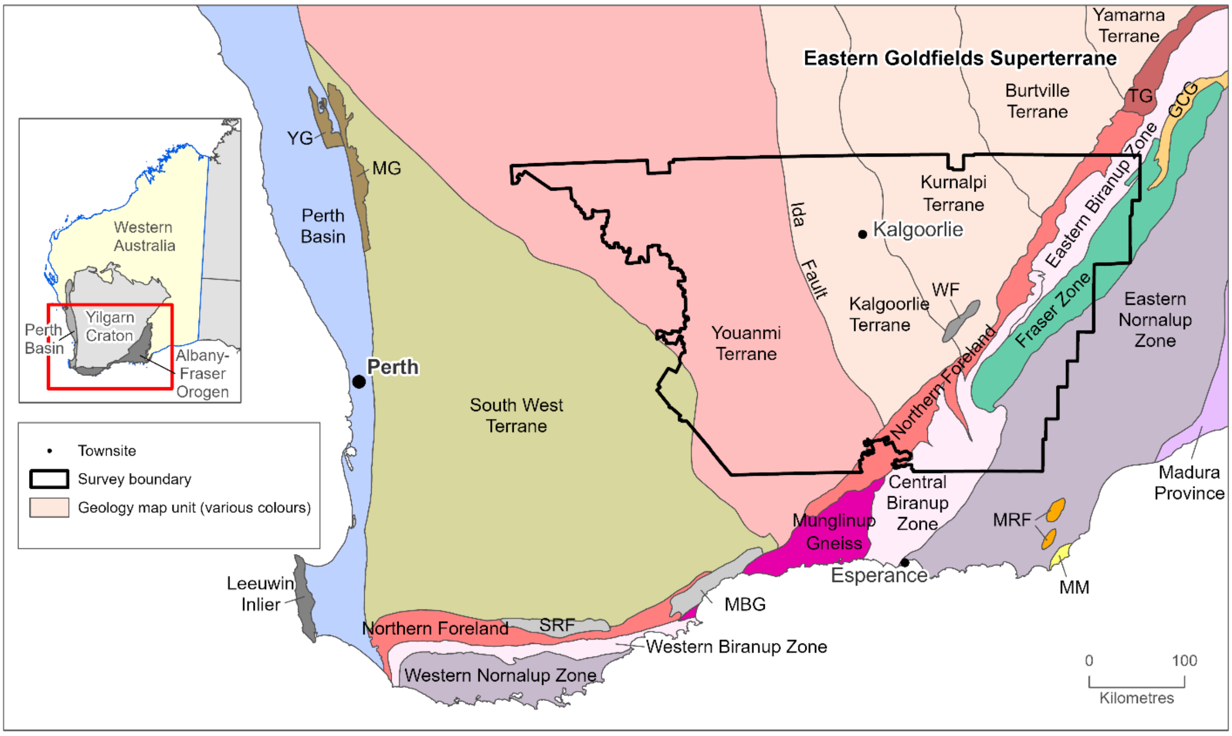
The reason for describing these aspects of the survey area is that the distribution of ecological communities (habitat types), their niches and soil minerals is determined by the processes outlined above, and are listed in more detail below:

- the chemical composition of primary (parent) rock and regolith materials
- tectonic processes influencing the distribution of parent materials and the surface topography
- the physical processes influencing the weathering, transport and deposition of alteration products of the above materials in new locations (geomorphic processes)
- the biochemical processes influencing the alteration of parent materials (climate, biology)
- evolutionary trajectory that promotes biotic processes that alter parent materials and soil conditions to best suit the lifeforms inhabiting the niches being altered
- feedback mechanisms that perturb the evolutionary trajectory and permit lifeforms to thrive or fail.

The spatial variation of soil and vegetation types at finer scale – ecotypes within each land zone – are separately described in the following chapters: Soils (Chapter 5), Vegetation and habitat type ecology (Chapter 6) and Land systems (Volume 2, Chapter 7).

Geology

The rocks of WA preserve elements spanning most of the Earth's evolutionary history. The survey straddles continental crust of the south-eastern part of the Archean Yilgarn Craton and the Proterozoic Albany-Fraser Orogen (Figure 4.1). The Yilgarn Craton is an ancient and stable shield that contains some of the oldest rocks preserved on Earth. It records a complex history that spans the generation and preservation of Earth's first solid minerals and rocks, modification of the early atmosphere and oceans by volcanism and early life, and creation, emplacement and destruction of minerals by an early mode of tectonics as the primary Earth-modification process (Mole et al. 2019). The complex Albany-Fraser Orogen is sutured to the south-eastern margin of the Yilgarn Craton and occupies the south-east portion of the survey area. It represents the initiation of modern-style plate subduction tectonic processes (Mole et al. 2019) with extensive reworking of Yilgarn crust and lateral accretion of new rocks by rifting, deposition, compression and subduction during the Proterozoic (Spaggiari et al. 2014a). The survey area's southern and eastern margins contain Phanerozoic sedimentary rocks formed when climate, tectonics and isostasy caused glacial ice, rivers and oceans to erode terrestrial surfaces and deposit materials on the inundated continental basement.



GCG = Gwynne Creek Gneiss; MBG = Mount Barren Group; MG = Moora Group; MM = Malcolm Metamorphics; MRF = Mount Ragged Formation; SRF = Stirling Range Formation; TG = Tropicana Gneiss; WF = Woodline Formation; YG = Yandanooka Group. Source: Adapted from Spaggiari et al. (2014b); Martin et al. (2020)

Figure 4.1: General geology of the southern Goldfields survey area

In addition to Phanerozoic sedimentary deposits of biological origin (e.g. limestones, spongolite), current understanding of the Earth's geological evolution implicate biota in the following:

- transformations and increasing complexity of mineral species (Hazen et al. 2008; Hazen 2010; Hystad et al. 2019)
- chemical transformation of Earth's Archean atmosphere and oceans (Catling and Zahnle 2020)
- production of Archean continental crust and increasing ratio of continental to oceanic crust of Earth's surface (Honing et al. 2014)
- formation of Archean and Proterozoic banded iron formations (Konhauser et al. 2017)
- initiation of modern plate tectonics (Parnell and Brolly 2021).

Furthermore, the emergence of the first macroscopic organisms and radiation of eukaryotes in the Proterozoic, as well as the proliferation of chlorophyte algae has been linked to early major periods of orogeny (mountain building) caused by plate tectonic processes (Zhu et al. 2022).

These insights represent a paradigm shift in our understanding of Earth's evolutionary history. Previously, it was thought that biota inhabited distinct geochemical environments over which it had little influence beyond passively living and dying within. Now, geological and mineralogical evolution is viewed as occurring concurrently and intimately associated with the increasingly complex web of life. As life has evolved to include evermore complex organisms, symbioses, communities and ecosystems, so too has the 'abiotic' component evolved in mineralogic complexity.

Yilgarn Craton

The Yilgarn Craton represents one of Earth's largest remaining remnants of Archean crust. Preserved within the craton are zircons dated to 4,400–2,730 Ma, which indicate reworked crustal components with possible Hadean ancestry (Wilde et al. 2001; Johnson et al. 2017; Mole et al. 2019). The craton results from 3 major episodes of emplacement of mantle rocks into the crust at circa 3,000–2,900, 2,800 and 2,700 Ma, which have interacted with continental crust older than 3,000 Ma (Witt et al. 2020). These tectonic processes have sequentially altered Earth's mineralogy, reworking hydrated mafic rocks to form sodic tonalite-trondhjemite-granodiorite (TTG) with subsequent reworking of TTG to form granodiorite-granite-monzogranite potassic granite (Mole et al. 2019). This process has progressively increased the proportion of silica and aluminium in continental crusts, making them less dense than hydrated mafic oceanic crust.

The relatively thin and buoyant continental crust of the Yilgarn Craton has an average thickness of about 35 km (Dentith et al. 2000; Reading et al. 2003; Sippl et al. 2017) and is underlain by a thick continental mantle root of high viscosity. To the north and east, the Yilgarn Craton is bounded by orogenic belts (Wang et al. 2016) that have served to preserve the craton from being recycled into the mantle by plate subduction processes, thus contributing to its long-term survival (Clitheroe et al. 2000). The relatively uniform crust and mantle thickness indicate the proto-craton formed in the absence of any significant compressional force, such as those associated with orogenic events (Rey and Houseman 2006; Flament et al. 2008; Smithies et al. 2019). The low density and high buoyancy of the craton have influenced geomorphic processes and the topography of surface landforms of the survey area, resulting in a stable terrestrial surface that has facilitated a long history of weathering and erosion. These factors have resulted in the region having a generally gently undulating and subdued topography. Regardless of the overall uniformity of the Yilgarn lithosphere, regional and local variations in thickness and tectonic structures (such as faults) control the placement of supracrustal (surface deposited) rocks.

The craton is divided into 2 major, geologically distinct parts by the Ida Fault, a major structure that extends to the base of the crust (Wyche et al. 2012). This significant north-trending lineament has a shallow (30°) eastward dip and is well defined for a length of 500 km (Swager et al. 1997; Weinberg and van der Borgh 2008). It separates the older western Yilgarn Craton – known as the South West Terrane – from the younger Eastern Goldfields Superterrane (EGST) to the east of the fault (Wyche et al. 2012; Mole et al. 2019) and delineates lithosphere-mantle boundary depths of 33 km for the western part and 38 km for the EGST (Swager et al. 1997). Its southern extent on the Yilgarn Craton is obscured by late-stage granitic intrusions (Sippl et al. 2017). The strike of the Ida Fault also coincides with distinct changes in lithosphere-mantle geometry of the Albany-Fraser Orogen (Sippl et al. 2017). Variations in lithosphere-mantle geometry influence tectonic processes, which consequently influence surface topographic and geomorphic characteristics across the region.

The Yilgarn Craton consists of 7 geological terranes, each comprising rock sequences of distinct age, geochemistry, sedimentary and magmatic characteristics (Cassidy et al. 2006;

Pawley et al. 2012; Mole et al. 2019).[1] Isotopic data indicate that the terrane subdivisions reflect regions with distinctive crustal histories (Wyche 2014 and references therein). The distinctive geochemical evolutionary sequence from mafic and ultramafic proto-crust to sodic (sodium-rich) TTG to granodiorite-granite-monzogranite potassic (potassium-rich) granites and syenite demonstrate the significant crustal evolution of the craton (Hazen et al. 2008; Smithies et al. 2019). At circa 2,720–2,600 Ma, the geological integrity of the craton was significantly consolidated when the older rocks of all the terranes were intruded by granites (Mole et al. 2019).

The western Yilgarn Craton constitutes the older portion (Yilgarn proto-craton) and comprises the Narryer, South West (comprising Balingup, Boddington and Lake Grace domains[2]) and Youanmi terranes. Evidence for ancient crustal sources, ascertained from isotopic data from zircons, and the presence of quartzites near the base of the greenstone succession is a common element of these 3 older terranes (Witt et al. 2020). In contrast, the EGST, of the eastern Yilgarn Craton, is distinctly more juvenile. It comprises accreted (but not exotic) terranes that have limited evidence of the forementioned ancient crustal sources (Wyche et al. 2012; Mole et al. 2019; Witt et al. 2020). Further evidence for distinction is provided from felsic rocks in the EGST with younger crustal sources aged less than 2,950 Ma, which are absent in the Yilgarn proto-craton with minor exceptions (Witt et al. 2020). These terranes are described below, except the Narryer Terrane as it lies well north of the survey area and is not mentioned further.

South West Terrane

The South West Terrane is the oldest within the survey area. It comprises ancient granitoid gneiss of igneous and sedimentary protolith, formed from reworking of primary mafic crust that originated in a proto-craton crustal growth event circa 3,700 Ma (Mole et al. 2019). The oldest known rocks of the South West Terrane are sodic TTGs, including the circa 2,980 Ma Manyutup tonalite (Mole et al. 2019) near Ravensthorpe, just outside the survey's south-western extent. These have been intruded by circa 2,750–2,620 Ma granites and pegmatites (Spaggiari et al. 2009; Mole et al. 2013).

Youanmi Terrane

The Youanmi Terrane lies east of the South West Terrane and retains ancient zircons greater than 4,000 Ma (Wyche et al. 2004; Mole et al. 2019). Youanmi Terrane differs from the South West Terrane in containing substantial greenstone belts separated by granite and granitic gneiss (Wyche et al. 2012). The boundary between the 2 terranes is poorly defined, a consequence of the late-stage granitoid magmatism throughout the area (Cassidy et al. 2006). The survey area lies over the Lake Johnston Block (Mole et al. 2013), which occupies the southern portion of the Southern Cross Domain, itself in the southern portion of the Youanmi Terrane. The age of the Southern Cross Domain is poorly constrained: the Ghoolie Dome west of Koolyanobbing records a protracted history of granitic magmatic activity from 2,775 to 2,625 Ma, while other granites and gneisses further east in the Southern Cross Domain are younger Archean rocks (Doublier 2013).

The Youanmi basement consists of moderate to strongly deformed granitic gneisses, granodiorite and monzogranite (Spaggiari et al. 2009) and retains evidence of zircons at least 3,200 Ma old (Hill et al. 1989). This basement was later overlain by intruding supracrustal rocks with a north-north-west trend (Mole et al. 2013). The basement and supracrustal Youanmi rocks

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1 A terrane is a very large, fault-bounded block containing rocks that have a distinct geologic history compared with contiguous blocks.

2 A domain is a distinct region with similar structural properties across its area.

were subsequently intruded by plutons of low calcium granitic composition (Spaggiari et al. 2009).

Four supracrustal greenstone belts are present in southern Youanmi Terrane. Koolyanobbing, Forrestania and Ravensthorpe greenstone belts lie at the western margin and are the oldest, formed between 3,000 and 2,900 Ma. Koolyanobbing has significant banded iron formation (BIF) within mafic and ultramafic volcanics; Forrestania and Ravensthorpe are dominated by mafic and ultramafic volcanics. The Lake Johnston greenstone belt lies further east towards the EGST, has a higher proportion of felsic volcanics, and is younger, formed at circa 2,875–2,775 Ma. The Ravensthorpe greenstone belt lies south-west of the survey area and is not mentioned further.

Koolyanobbing greenstone belt

The Koolyanobbing greenstone belt is 8 km wide and extends north-west for about 35 km between Lake Deborah to the north and Lake Seabrook to the south. The surrounding rocks in the south-west are gneisses of the Ghooli and Lake Deborah domes, and banded gneisses in the north-east. This greenstone belt is the oldest volcano-sedimentary succession of the Youanmi and has a minimum age of circa 3,023 Ma (Angerer et al. 2013). It comprises 4 volcano-sedimentary sequences that are more dominantly mafic and ultramafic than other Yilgarn greenstone belts.

The first sequence consists mostly of basalt metamorphosed to schistose amphibolites and ultramafic komatiite layers with minor interbedded BIF, chert and metamorphosed sandstone (quartzite). The second sequence consists of basalts with interbedded quartzite and minor BIF/chert sequences, overlain by a prominent BIF unit about 200 m thick. The third sequence contains metabasalt and a BIF unit less than 30 m thick with interbedded clastic and sandy metasediments. The fourth and uppermost sequence is 800 m thick and consists of thick ultramafic komatiitic basalt interlayered with mafic volcanic rocks.

Forrestania greenstone belt

The Forrestania greenstone belt, on the western margin of the survey area, trends north–south and has a synclinal structure formed under amphibolite metamorphic conditions (Chin et al. 1984). It comprises 2 major successions. The lower succession is 3–5 km thick and dominated by metamorphosed mafic and ultramafic volcanic rocks, interlayered with metamorphosed BIF and chert (Chin et al. 1984; Perring et al. 1995). There are at least 4 komatiite sequences in this lower succession, containing both aluminium-depleted and aluminium-undepleted komatiites (Perring et al. 1996). The upper succession is 3–5 km thick and comprises pelitic and psammitic schists (Chin et al. 1984; Perring et al. 1995).

Lake Johnston greenstone belt

The Lake Johnston greenstone belt is the youngest and eastern-most of the southern Youanmi greenstones. It is bound by the Tay Fault in the west and the Koolyanobbing Fault in the east (Spaggiari et al. 2009). Deposited in a submarine setting during major tectono-thermal events, the early supracrustal greenstone emplacements consist of basalts of the Maggie Hays Formation, overlain by felsic volcanic sediments and BIF of the Honman Formation, and then ultramafic komatiites and mafic basalts of the Roundtop and Glasse formations, respectively (Romano et al. 2014). Emplacement concluded with the intrusion of the Lake Medcalf Igneous Complex, consisting of mafic and ultramafic gabbro, pyroxenite and leucogabbro (Romano et al. 2014).

Eastern Goldfields Superterrane

The EGST occupies the eastern portion of the Yilgarn Craton. It represents a circa 2,735–2,690 Ma crustal growth event along the eastern rifted margin of the proto-Yilgarn Craton (Mole et al. 2019). The EGST is bounded by the Capricorn Orogen to the north and by the Albany-Fraser Orogen to the south and east. It is divided into 4 fault-bounded tectonostratigraphic terranes: Kalgoorlie, Kurnalpi, Burtville and Yamarna, from west to east (Wyche et al. 2012; Mole et al. 2019). While many publications subdivide the EGST into 4 terranes, some also recognise different lithological associations and a fifth terrane, Gindalbie, situated between the Kalgoorlie and Kurnalpi terranes (Barley et al. 2008; Witt et al. 2020); here, we only refer to the 4 main terranes. The Kalgoorlie, Kurnalpi and Yamarna terranes are considered contemporaneous and younger than the Burtville Terrane, which has more in common with the Murchison Domain to the north-west of the Youanmi Terrane (Pawley et al. 2012). Yamarna is the eastern-most terrane of the Yilgarn and is significantly blanketed by Phanerozoic sediments. It is separated from the adjacent Burtville Terrane by the Yamarna Shear zone. The Yamarna Terrane lies north-east of the survey area, so it is not mentioned further. The north-east of the survey area coincides with the southern extent of the Burtville Terrane. Here, Burtville bedrock is mostly granite to adamellite and migmatite. Regolith cover is extensive, so rock outcrop is sparse and exposures are rare. Outcrops are often weathered, silicified and/or ferruginous (Bunting and van de Graaff 1977).

The Kalgoorlie and Kurnalpi terranes of the EGST formed in the Kalgoorlie-Kurnalpi rift that separated the Burtville Terrane from the western Yilgarn proto-craton circa 2,700 Ma (Mole et al. 2019; Witt et al. 2020). Kalgoorlie and Kurnalpi terranes lie east of the Ida Fault and are highly mineralised granite–greenstone terranes with world-class deposits, especially gold and nickel (Wyche et al. 2012). Both terranes lack thick BIF units (Mole et al. 2013). The granite domes and greenstone belts have a broad north-north-west orientation aligned with the underlying tectonic structure. All supracrustal rocks were emplaced during major rifting and plume-related volcanic events associated with TTG magmatism (Wyche et al. 2012; Witt et al. 2020). The oldest volcanic sequences (>2,750 Ma) are present across both terranes and are dominated by basalt and komatiite, and also contain minor rhyolite. Granitic intrusions presumably represent uplifted portions of basement rock (Witt et al. 2020). Distinct greenstone sequences, which distinguishes Kalgoorlie from Kurnalpi, were laid down between circa 2,720 and 2,660 Ma.

The greenstones of the Kalgoorlie Terrane are substantial, extending from Norseman to Wiluna, and contain voluminous volcanic sequences that accumulated in marine to emergent settings. The first and older sequence comprises thick layers of mafic and ultramafic successions laid down circa 2,710–2,690 Ma, followed by minor intermediate to felsic volcanics laid down circa 2,690–2,660 Ma (Wyche et al. 2012; Witt et al. 2020). The basal member of the corelated greenstone units is a thick basalt sequence – at least 1,750 m thick and up to 5,000 m – that consists of multiple thin lava flows and minor interflow sedimentary rocks (Squire et al. 1998; Neumayr et al. 2004). This is overlain by multiple, texturally diverse komatiite layers with occasional contemporaneous dacitic felsic volcanics and volcaniclastics interbedded through some areas (Witt et al. 2020 and references therein). The uppermost greenstone member consists of basalt units, which in the Kalgoorlie and Kambalda area is separated into 2 units by a metasedimentary unit, the Kapai Slate (circa 2,792 Ma). These upper sequence basalts achieve thicknesses of up to 2,000 m and range from variously developed massive and pillowed basalts around Kambalda, to dolerite and gabbro around Ora Banda (Witt et al. 2020). Unconformably overlying this mafic–ultramafic succession is a volcano-sedimentary sequence known as the Black Flag Group. This sequence is over 3,000 m thick and comprises extensive volcaniclastic rocks of rhyolitic to dacitic composition, intrusive mafic complexes and minor mafic volcanic rocks (Wyche et al. 2012; Witt et al. 2020). Although some sequences do not occur throughout the terrane, typically the basal member is feldspar-rich volcaniclastic sandstone and siltstone overlain by andesitic breccia, conglomerate and sandstone, and then by feldspathic sandstone and siltstone, carbonaceous shale and minor felsic volcanics (Witt et al. 2020).

The final stage of supracrustal emplacement across the Kalgoorlie and Kurnalpi terranes was the unconformable deposition of poorly sorted sandstone and conglomerate over greenstone and granite in late-stage Archean (<2,665 Ma) fluvial and deep marine sedimentary basins. These also contain minor black shales, laminated green mudstones and chert (Krapez and Barley 2008; Krapez et al. 2008a, 2008b; Wyche et al. 2012). Examples of such sedimentary sequences within the survey area include the Kurrawang Formation in the Kalgoorlie Terrane and the Pig Well-Yilgangi Basin in the Kurnalpi Terrane. The development of sedimentary basins is associated with regional faulting, which coincided with the transition from high calcium to low calcium granite magmatism during the late stages of the Yilgarn Craton's formation (Mole et al. 2019; Witt et al. 2020).

The boundary between Kalgoorlie and Kurnalpi terranes is complex. For example, volcanic sequences from both Kalgoorlie and Kurnalpi terranes are tectonically interlayered along the eastern margin of the Bulong Domain (Cassidy et al. 2006). The oldest greenstone sequence unique to the Kurnalpi Terrane is circa 2,720–2,710 Ma and is dominated by calc-alkaline andesitic volcanics and volcaniclastic products (Witt et al. 2020). This sequence derives from marine to locally emergent volcanic centres in eastern Kurnalpi that erupted basaltic to andesitic lavas with minor dacite and rhyolite. Volcaniclastic and sedimentary facies grade outwards from the volcanic centres to later form sandstone, siltstone and lenses of conglomerate, intruded by dolerite sills (Witt et al. 2020). Komatiite and basaltic flows are also present as thin sequences occupying former landscape depressions (Wyche et al. 2012; Witt et al. 2020). A younger (circa 2,690–2,680 Ma) greenstone sequence in the Kurnalpi Terrane, restricted to the western Gindalbie Domain, is characterised by a linear belt of bimodal volcanism. Here, basalt–andesite units are interbedded with dacitic–rhyolitic lavas and volcaniclastic deposits over calc-alkaline rocks (Cassidy et al. 2006; Witt et al. 2020).

The final stage of cratonisation occurred during the late Archean, when all earlier Yilgarn Craton rocks were intruded and variably metamorphosed by granite plutons in a series of heat-pulse events (Czarnota et al. 2010; Mole et al. 2019). Neoarchean to Paleoproterozoic tectonic activity emplaced other igneous intrusions into the Yilgarn Craton along the south-eastern margin of the EGST. Between Salmon Gums and Norseman near Peak Charles National Park, common quartz syenite, which grades to biotite adamellite, was emplaced (de Laeter and Lewis 1978). These subsequently became exposed by erosion and form the prominent syenite inselbergs of Kartukartunga (peaks Charles and Eleanora). Other prominent features transecting through much of the south of the Yilgarn Craton and southern Goldfields region are igneous dykes associated with the Widgiemooltha Dyke swarm. These Paleoproterozoic (circa 2,408 Ma; Wingate 2017; Stark et al. 2019) linear dykes trend east-north-east to west-south-west. The largest intrusions are the Binneringie and Jimberlana dykes, that have lengths and maximum widths of 600 km and 3.5 km, and 180 km and 2.5 km, respectively. They typically display rhythmic or phase layering and, aside from narrow chill margins and minor contact metamorphic aureoles, are largely unmetamorphosed. Binneringie is mainly gabbroic, but also locally preserves intermediate and granophyric phases. Jimberlana is divided into 2 layered series and consists of gabbro, gabbronorite, pyroxenite, peridotite, norite and dolerite (Doepel 1973; Hall and Jones 2008). Numerous hydrothermal quartz dykes and veins of variable size and extent, intruding and intersecting the country rock, in places concentrating ores to economically viable concentrations also occur throughout the region.

Syenite inselberg of Kartukartunga (Peak Charles)

Linear expression of Jimberlana dyke along Jimberlana Hill

Albany-Fraser Orogen

The Albany-Fraser Orogen (AFO) extends over 1,200 km along the southern and south-eastern margin of the Yilgarn Craton, dominating most of the south-eastern portion of the survey area. The AFO is interpreted as the Proterozoic modification of Archean-age Yilgarn Craton crust (Spaggiari et al. 2011).

Tectonic events in the Neoarchean and Paleoproterozoic were the precursors for the AFO evolution. These events include widespread magmatism, the formation of sedimentary basins, and high-temperature metamorphism and deformation. Based on current geochronologic dates (Quentin de Gromard et al. 2017 and references therein), tectonic events commenced circa 2,722 Ma with numerous events preceding the Paleoproterozoic Biranup Orogeny (1,710–1,650 Ma) and culminating in the Mesoproterozoic Albany-Fraser Orogeny (1,330–1,140 Ma). The Albany-Fraser Orogeny is further divided by 2 tectonic events: Stage 1 (1,330–1,260 Ma) and Stage 2 (1,225–1,140 Ma).

The Archean rocks of the Yilgarn Craton are separated from the modified, mixed rocks of the AFO by the Jerdacuttup and Cundeelee thrust faults (Spaggiari et al. 2011). Within the AFO there are 2 main tectonic units — the Archean Northern Foreland and the younger Paleoproterozoic to Mesoproterozoic Kepa Kurl Booya Province — distinguished by their structural position and degree of craton modification (Spaggiari et al. 2014a, 2014b; Sippl et al. 2017). Supracrustal sedimentary rocks, derived from Archean and Proterozoic sources, were deposited in 3 long-lived sedimentary basins that developed coeval with the orogenic activity that formed the Proterozoic basement (Spaggiari et al. 2014b). The 3 sedimentary basins within AFO are: the circa 1,815–1,600 Ma Barren Basin; the circa 1,600–1,305 Ma Arid Basin (Spaggiari et al. 2014b); and the circa 1,314–1,175 Ma Ragged Basin (Waddell et al. 2015), though only limited exposures of Barren and Arid basin sediments are present in the survey area. All basin sediments have been variably metamorphosed, ranging from greenschist to granulite facies.

It is envisaged that the AFO developed as part of a Paleoproterozoic continental rift or distal back-arc setting followed by intracratonic orogenesis in several episodes (Spaggiari et al. 2014b).

Northern Foreland

The Northern Foreland is the margin of the Archean Yilgarn Craton that was intruded by Paleoproterozoic magmatic rocks and then reworked during the Mesoproterozoic Albany-Fraser Orogeny (Spaggiari et al. 2014a). It consists of greenschist and amphibolite to granulite facies, Archean gneisses and granites, remnant greenstones and younger dolerite dykes (Spaggiari et al. 2014a). Within the survey area, rocks of the Northern Foreland comprise metagranite units, such as metamonzogranite and granitic gneiss. To the south, outside the survey area, the major component comprises higher metamorphic grade rocks belonging to the Munglinup Gneiss, which is an amphibolite to granulite facies orthogneiss interlayered with lenses of metamorphosed mafic rocks (Spaggiari et al. 2014a). Geochronological data from granitic gneiss indicate it was derived from Neoarchean protoliths having magmatism dates ranging between circa 2,720 and 2,620 Ma, which is comparable to magmatism in the Yilgarn Craton (Quentin de Gromard et al. 2017 and references therein).

Kepa Kurl Booya Province

The Kepa Kurl Booya Province in the south-east represents lateral accretion of new crust during the Paleo- to Mesoproterozoic and forms most of the AFO. In the survey area, it is subdivided into the Biranup, Fraser and Eastern Nornalup zones. The Paleoproterozoic Biranup and Eastern Nornalup zones are dominated by granitic gneisses initially formed during 2 major magmatic events: the Salmon Gums Event (1,815–1,800 Ma), which corresponds to the early developmental stages of the Barren Basin; and the Ngadju Event (1,780–1,760 Ma), which corresponds to widespread sediment deposition and sub-basin formation within the Barren Basin (Spaggiari et al. 2014b; Quentin de Gromard et al. 2017). In contrast, the Mesoproterozoic Fraser Zone is dominated by voluminous sheets of metagabbro and less abundant metagranite rocks that have undergone high-grade metamorphism. A significant component is the 1,305–1,290 Ma Fraser Range Metamorphics, which comprise metagabbroic rocks interlayered with metamonzogranite to metasyenogranite, pyroxene-bearing granitic gneisses, and hybrid magmatic rocks with metasedimentary sequences (Spaggiari et al. 2014a).

All Kepa Kurl Booya rocks have been intruded by younger granitic rocks in the 2 tectonic events (Stages 1 and 2), which represent the Albany-Fraser Orogeny (Spaggiari et al. 2011). During Stage 1 (circa 1,330–1,276 Ma) the Recherche Supersuite was emplaced, which coincided with granite emplacement within the Fraser Zone. A second period of granite emplacement, the Esperance Supersuite, occurred during Stage 2 (circa 1,198–1,140 Ma; Quentin de Gromard et al. 2017 and references therein).

Exposed rocks from the Fraser Zone along the Fraser Range

Barren Basin

The Barren Basin comprises Paleoproterozoic metasedimentary rocks that overlie the Yilgarn Craton, Northern Foreland and the Biranup and Nornalup zones. When considered as a distinct system, the Barren Basin extended up to 1,000 km along the southern and south-eastern Yilgarn Craton margin, during its evolution over more than 200 million years (1,815–1,600 Ma; Spaggiari et al. 2014b). The associated few landforms that punctuate the present land surface are interpreted to be the structural and erosional remnants of this much larger basin system that evolved during the Late Paleoproterozoic. Most remaining sedimentary units are derived mostly from detritus shed from the Yilgarn Craton. They comprise quartz-rich lithologies including cross-bedded sandstones, clean sandstones, pebbly sandstones and siltstones. These sandy sediments have been metamorphosed to quartzites (Spaggiari et al. 2014b).

Barren Basin metamorphosed sedimentary deposits within the survey area are the Woodline Formation (Woodline Sub-basin), the Fly Dam Formation and the Ponton Creek psammitic gneiss. The most prominent is the Woodline Formation that comprises quartz-rich sandstone, pebbly-conglomerate and siltstone, and expresses as north-east trending hills and rises (Hall and Jones 2008). The Woodline Formation unconformably overlies granite and greenstone of the EGST (Hall and Jones 2008). Deposited in the Woodline Sub-basin between circa 1,651–1,600 Ma (Quentin de Gromard et al. 2017), the depositional setting is interpreted as a distal fluvial to fluvial–deltaic–shallow marine environment (Hall and Jones 2008; Spaggiari et al. 2014b). The sediments have been altered to quartzite and chert, but sedimentary structures remain well preserved (Hall and Jones 2008).

The other Barren Basin sedimentary deposits In the survey area have limited exposure. The Fly Dam Formation outcrops on Coonana pastoral lease and the Ponton Creek psammitic gneiss outcrops near Ponton Creek. Both occur in the Eastern Biranup Zone. The Fly Dam Formation comprises interbedded sandstones and mudstones, metamorphosed to amphibolite to granulite facies to form psammitic to semipelitic gneisses (Spaggiari et al. 2014b). The Ponton Creek psammitic gneiss displays fine laminations and cross-bedding structures. It contains potassium-feldspar (60%) and quartz (35%), and minor garnet and biotite (Kirkland et al. 2010). Other prominent Barren Basin metasediments outside the survey area include the Stirling Range Formation and the Mount Barren Group.

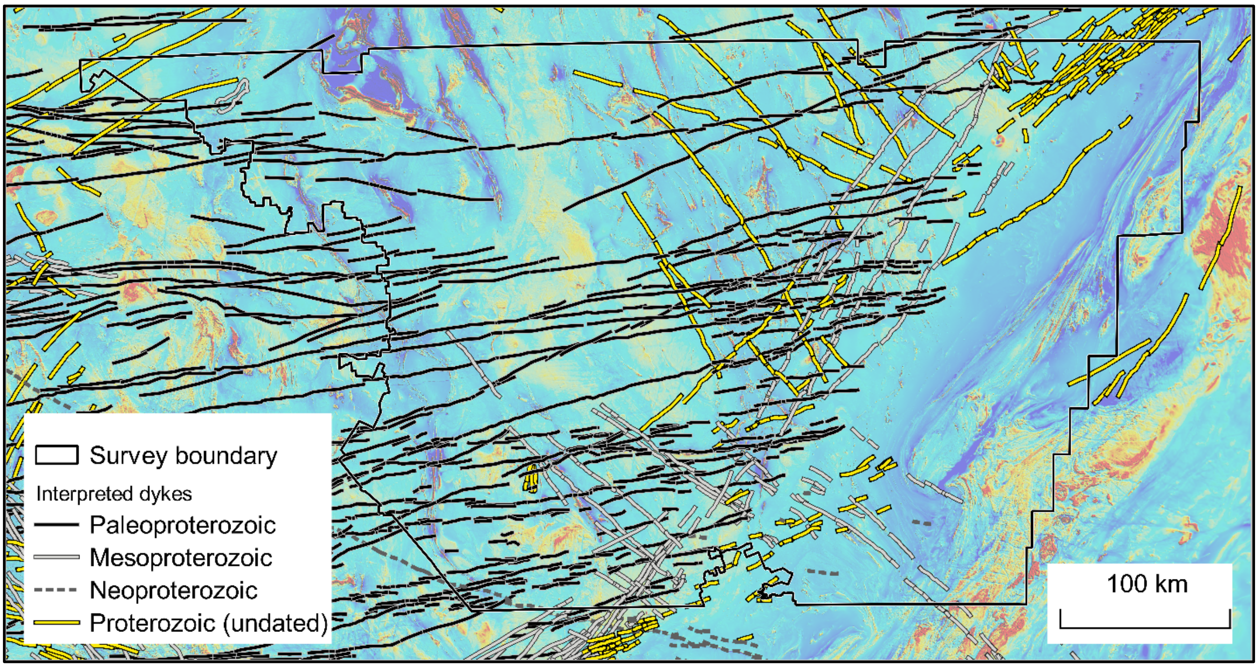
Arid Basin

The tectonic setting and depositional environment of the Arid Basin contrasts significantly to that of the Barren Basin. The Arid Basin sedimentary deposits are extremely variable and include interbedded sandstone and mudstone, calcareous rocks or marls, iron-rich horizons, and volcaniclastic or volcanic successions (Spaggiari et al. 2014b). These deposits lack evidence of fluvial deposition but do exhibit subparallel layers of mafic and calc-silicate rocks emplaced together during magmatic events (Spaggiari et al. 2014b).

The sole known Arid Basin unit within the survey area is from limited exposures belonging to the Snowys Dam Formation south of Fraser Range. Exposures of this formation mostly occur along the western side of the Fraser Zone to the north-east of the survey area (Spaggiari et al. 2014b). The Snowys Dam Formation is the name for the metasedimentary rocks of the Fraser Range Metamorphics (Spaggiari et al. 2014b). It is mostly garnet-rich pelitic and semipelitic gneisses with locally iron-rich horizons and quartz-rich psammitic gneiss. These metasedimentary sequences are often intercalated with layers and sills of mafic granulite or amphibolite that are interpreted as Fraser Zone gabbroic intrusions (Spaggiari et al. 2014b).

Proterozoic mafic dykes

Three Proterozoic dyke suites (besides the previously described Archean–Proterozoic Widgiemooltha Dyke Suite) are recognised: Gnowangerup–Fraser, Nindibillup and Beenong (Figure 4.2). The Gnowangerup–Fraser Suite extends across the southern and south-eastern parts of the Yilgarn Craton and AFO. The suite is part of the large, circa 1,210 Ma, igneous Marnda Moorn Province and typically consists of north-easterly trending dykes composed of dolerite, gabbro and quartz diorite (Spaggiari et al. 2009). The Nindibillup Dyke Suite trends east to south-easterly and cuts across major features within the AFO (Spaggiari et al. 2009). It is dated at circa 735 Ma (Wingate 2017). The Beenong Dyke Suite trends north-westerly and little is known of its composition or age, although based on cross-cutting relationships, it is likely younger than 1,140 Ma (Spaggiari et al. 2009; Spaggiari et al. 2011).



Notes:

1. The magnetic signature shows structural differences between the Yilgarn Craton, which occupies most of the survey area, and the Albany-Fraser Orogen, which occupies the eastern portion.
2. Dykes are common across the Yilgarn Craton and rare within the Albany-Fraser Orogen.
3. Many of the dykes present in the southern part of the Yilgarn Craton were emplaced at the same time as the Esperance Supersuite granites of the Albany-Fraser Orogen.

Data sources: Dykes (Martin et al. 2020); total magnetic intensity (Brett 2017)

Figure 4.2: Mapped Proterozoic dykes of the survey area overlaid on the magnetic signature of bedrock

Phanerozoic sediments

Paleozoic sediments

Glacial deposits of the Paleozoic Canning–Officer Basin Complex occur in the far east and north-east of the survey area (Bunting and van de Graaff 1977; Mory et al. 2008). Though outcrop is generally sparse, there are some good exposures of Permian glacial deposits from the Paterson Formation in Ponton Creek. Typically, these deposits comprise thin, near-horizontal beds of basal diamictite (tillite) overlain by mudstone and sandstone sequences (Bunting and van de Graaff 1977; Mory et al. 2008). In places, glacial tillite is overlain by lacustrine sediments, interpreted as glacial lake deposits (Bunting and van de Graaff 1977). The Permian deposits are mainly associated with the Eucla Basin and are mostly restricted to paleovalleys that subsequently became reactivated during the Mesozoic when they drained east and south into the developing Australo-Antarctic Gulf (Clarke 1994; Clarke et al. 1996; Beard 1999; Hall and Jones 2008).

Cenozoic sediments

Cenozoic sediments within the survey area overlie Permian deposits, and Archean and Proterozoic crystalline basement. Much of the south-east has been affected by changes in sea level (marine transgressions and regressions) associated with the widening Australo-Antarctic Gulf and evolution of the Eucla and Bremer basins (Clarke et al. 2003; see Geomorphology section and the Climate chapter). Repeated transgressions and regressions have resulted in sequences of fluvial, lacustrine and shallow marine deposits that typically form a shallow veneer of near-horizontal sediments (Clarke et al. 2003), which are locally thicker within paleovalleys (Hocking 1990a, 1990b; Clarke 1994). Planation by marine erosion has further shaped the present land surface.

Eundynie Group

The Eundynie Group is a sequence of sedimentary rocks deposited during the Tortachilla and Tuketja marine transgressions, in the Early to Middle Eocene and the Late Eocene respectively (Clarke et al. 1996; Hall and Jones 2008). This group contains fluvial–deltaic, estuarine and marine sediments comprising a range of facies including poorly sorted fine-grained to medium-grained sandstone, interbedded siltstone and mudstone, granular conglomerate and spongolite (Griffin 1989; Hall and Jones 2008). Outcrop is often deeply weathered, iron-stained and silicified, and is frequently capped by calcrete, ferricrete or silcrete.

Various sediments are assigned to the Eundynie Group. The sediments are considered laterally equivalent, but each deposit is regarded as a different formation because they were laid down in separate paleochannels with distinct depositional environments. In the Lefroy paleodrainage, the Eundynie Group consists of the Hampton Sandstone, Pidinga Formation and Princess Royal Spongolite. In the Cowan paleodrainage, the Eundynie Group consists of the Werillup Formation, Norseman Limestone and Princess Royal Spongolite (Clarke 1993). The Werillup Formation in the Cowan paleodrainage is laterally equivalent to the Hampton Sandstone and Pidinga formations in the Lefroy paleodrainage (Clarke 1994). Lignite is more common in the Werillup Formation than in the Hampton Sandstone and the Pidinga Formation.

The Lefroy paleodrainage lies to the north of Lake Cowan and drained to the east into the Eucla Basin. During the Tortachilla (40–38 Ma) transgression, the Hampton Sandstone and Pidinga Formation were deposited in the Lefroy paleodrainage. The Hampton Sandstone consists of sand and gravel deposited in a high energy nearshore environment. It contains fossils of marine fauna and siliceous and calcareous sponge spicules. However, the sequence varies locally because siliceous sponge spicules are absent from tributary paleodrainage channels or locations inferred to be remote from high energy sedimentary environs. The Pidinga Formation has both lignite and silty clay deposits containing Early–Late Eocene palynomorph assemblage and is interpreted as floodplain and channel sediments deposited in a rainforest deltaic environment (Clarke 1994).

The Cowan paleodrainage is the southern-most within the survey area. It formed a long, narrow paleovalley that drained south to the Eucla and Bremer basins in the widening Australo-Antarctic Gulf (see Paleoclimate section in the Climate chapter). The Tortachilla transgression flooded the Cowan paleovalley, forming a long estuary (Clarke et al. 1996; Gammon and James 2003) into which the Werillup Formation was deposited. The Werillup Formation has sandy, silty, lignitic and spicular lithologies and can be up to 40 m thick. The interlayered siliceous sponge spicules indicate partial shallow marine deposition. The Werillup Formation is interpreted as floodplain and channel sediments in a rainforest deltaic and marginal marine mangrove environment (Clarke 1994). During transgressive to highstand phases of the Tortachilla transgression, the Norseman Limestone was interlayered with the upper layers of the Werillup Formation (Clarke et al. 1996). It is a sandstone and calcareous sandstone to limestone sequence contemporaneous with the Werillup Formation.

During the Tortachilla transgression, a marine gulf protected by barrier islands lay seaward of the estuary of the Cowan paleovalley. Sediments that form the Pallinup Siltstone were deposited into this gulf circa 40–38 Ma. Pallinup Siltstone is the marine equivalent of the Werillup Formation. It is a light-coloured, banded, silty sandstone to siltstone containing siliceous spicules and mollusc fossils. Pallinup Siltstone may overlie Werillup Formation or unconformably overlie AFO granites. It is widespread across the southern margin of the survey area.

The Late Eocene (circa 38–39 Ma) Tuketja transgression flooded both Cowan and Lefroy paleovalleys and resulted in enclosed estuaries with shallow, calm, warm waters conducive to marine sponge proliferation (Clark et al. 1996; Gammon and James 2003). This environment accumulated siliceous bio-spicules, silt and clay sediments, forming the Princess Royal Spongolite (Clarke et al. 1996).

Post-Eocene deposits

A Late Oligocene to Miocene transgression represents the final marine influence within the survey area, and only limited surface exposures have been identified. The Colville Sandstone is represented by one fossiliferous example in the north-east of the survey area at 50 Mile Claypan (Mindat 2021). Deposited at the same time and laterally along the margin of the regionally extensive Nullarbor Limestone of the Eucla Basin, the Colville Sandstone is dominated by calcareous sandstone (Lowry 1970).

As sea levels regressed across the region, estuaries receded to form lake chains. In the Cowan and Lefroy paleodrainage systems, this regression was accompanied by deposition of the fluvial–lacustrine Redmine Group, overlying the Eundynie Group. The Redmine Group mainly comprises the clastic Revenge Formation which consists predominantly of fine-grained facies of red–brown silts and clays, and coarse-grained sand facies (Clarke 1994). Limited carbonate units within the Redmine Group comprise the Cowan Dolomite in Lake Cowan and the Gnamma Island Formation in Lake Lefroy (Clarke 1993). Deposition of the Redmine Group probably took place during the Miocene (Clarke 1993). From the Pliocene onwards, increasing aridity led to deposition of the gypsiferous Polar Bear Formation in Lake Cowan and the Roysalt Formation in Lake Lefroy (Clarke 1994). These evaporitic deposits were reworked by eolian processes to form gypsum and sand lunettes and dunes along lake margins.

Other Quaternary deposits mainly consist of unconsolidated sediments comprising lacustrine, alluvial, eolian and colluvial materials subjected to contemporary reworking processes.

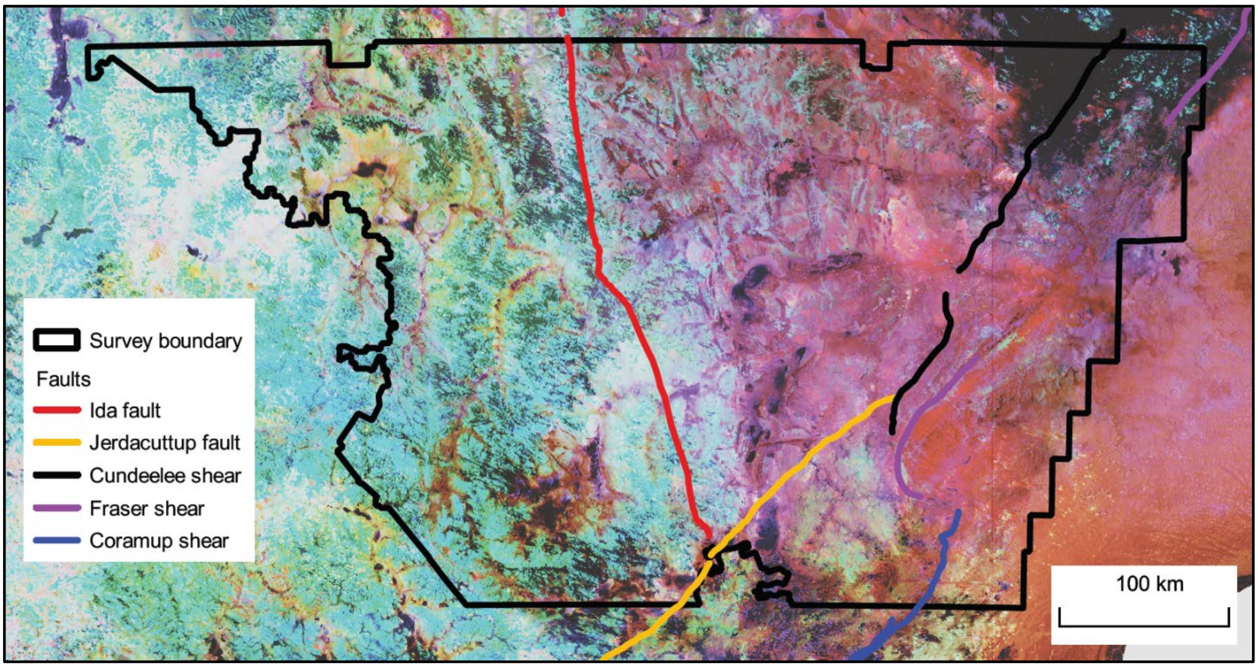
Geomorphology

The following section provides information relevant to drivers of landscape formation in the southern Goldfields region. Information relates to how geological structural characteristics, such as faulting, and deep-earth processes along with superficial physical, biochemical and chemical processes influence weathering, erosion and deposition, and so influence landscape evolution.

Geological influences on topography

Rock structure and physicochemical conditions of formation significantly influence topographic development. Granite has high silica content, large crystal size and high coherence which makes it resistant to erosion, so it often forms domed hills and rises. The variable hardness and chemistry of greenstone sequences contribute to differences in relative relief within greenstone terranes. Metamorphosed sedimentary rocks, such as BIF and quartzite, are highly resistant to weathering and form ridges to high hills, depending on their depositional volume and tectonic-induced orientation. Basalt is also resistant as it forms relatively large masses of weakly-fractured or unfractured rock. Basalt and gabbro hills, such as Jaurdi Hill, form from mafic volcanic plugs and stand proud of the surrounding plains. In contrast, ultramafic and volcaniclastic rocks are highly weatherable and erodible, so water preferentially flows along these sequences, forming depositional landforms and valleys (Clarke 1994).

Siliceous magmas (rich in silica and aluminium) scavenge thorium and uranium and therefore concentrate these radioisotopes. Concurrently, this depletes the remaining mafic magma of these elements. During craton formation, as crust was repeatedly recycled to form ever more siliceous granites, the resulting rocks became progressively enriched in thorium and uranium (Hazen et al. 2009). A consequence of this scavenging process was that mafic and ultramafic rocks formed from the remaining depleted mantle, so lack these radioisotopes. These isotopic enrichment and depletion processes are apparent in the ternary colour radiometric image of the survey area, which illuminates the significant differences in rock mineralogy west and east of Ida Fault (Figure 4.3).



Notes:

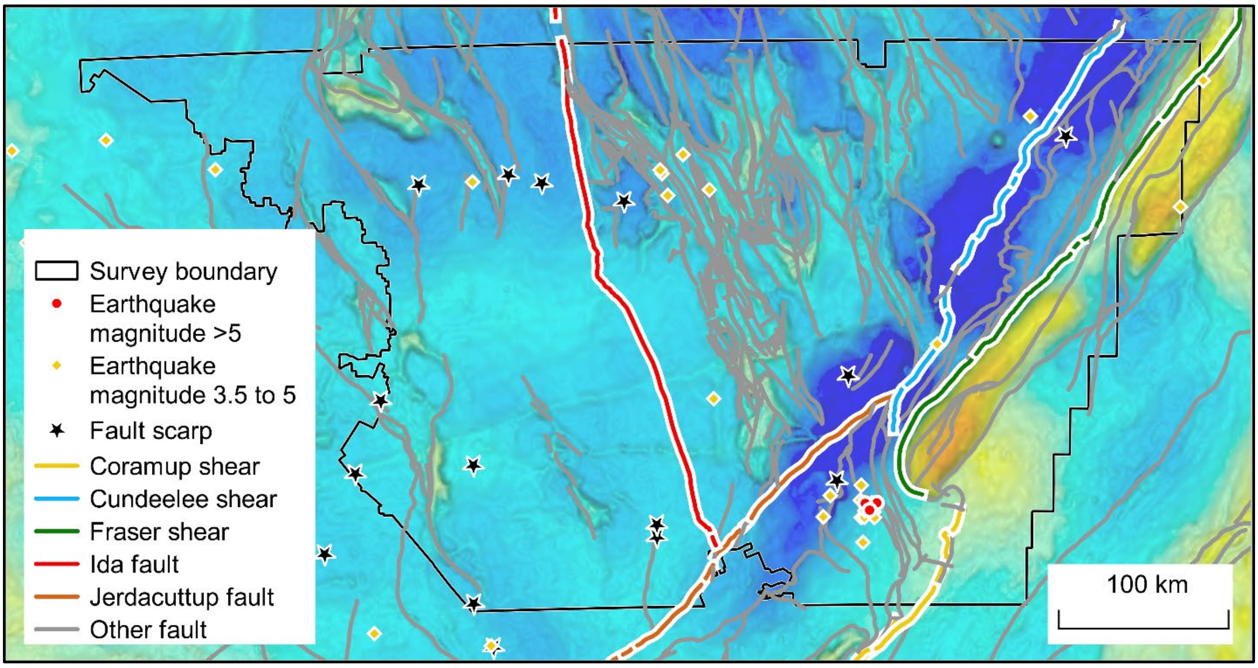
1. Red = high potassium; green = high thorium; blue = high uranium; white = high in all 3 radioisotopes; black = not radiogenic (often means leached, having gone through a weathering cycle).
2. Potassium co-concentrates with marine sources of calcium carbonate, which explains the high potassium signal of the Nullarbor Plain and areas within the survey affected by marine transgressions.
3. Uranium and thorium co-concentrate with iron concretions in soil (see Soils chapter), which explains the cyan colour along Ida Fault and westwards, for example.
4. Uranium is immobile in anoxic conditions, but potassium and thorium are mobile and become leached, which explains the deep blue colour of Lake Dundas located in the low centre of the image.

Data sources: Faults (Martin et al. 2020); ternary radiometric image (Brett 2018)

Figure 4.3: Major faults of the survey area overlaid on the ternary radiometric image

The image shows the concentration of 3 radioactive isotopes: potassium (red), thorium (green) and uranium (blue); white colours represent high concentrations of all 3 elements, and black represents no radioisotopes present. Potassium is an abundant element in the lithosphere and is a significant element in many minerals of crystalline rocks. The greenstone rocks and soils of the EGST derive from mantle material depleted in thorium and uranium but retain much potassium, and so display as red. In contrast, granites of the southern Youanmi Terrane are enriched in thorium and uranium and retain potassium, so these display as white. Aqua areas show soils forming from granite, whose potassium content is becoming less as the rock weathers, but whose uranium and thorium levels remain elevated.

Numerous long-lived faults and shear zones transect the area, and their orientation reflects the tectonic history of the bedrock (Figure 4.4). Faults and shear zones function as foci for mineral deposits and as zones of structural weakness that permit preferential weathering and function as conduits for subterranean and surface water.



Notes:

1. Cool colours are low mass, warm colours are high mass.
2. There is a significant gravity divergence at the western and southern margin of the Fraser Zone, which orients north-east along the eastern border of the survey area.
3. The Fraser Zone's south-western extent is the focus of current intracratonic earthquake activity.

Data sources: Fault structures (Martin et al. 2020); earthquakes (Geoscience Australia National Earthquakes Alerts Centre 2021); surficial fault scarps (Clark 2010); gravity anomaly image (Brett 2019)

Figure 4.4: Gravity-inferred fault structures, earthquakes between 2010 and 2021, and surficial fault scarps of the survey area overlaid on gravity anomaly data

Faults of the Archean Yilgarn Craton align north-north-west in association with major terrane boundaries and greenstone belts. The Ida Fault is a dominant structural feature of the southern Yilgarn Craton. It has locally influenced geomorphology and soil formation by acting as a conduit and facilitating deep exploration of regolith by the roots and fungal associates of plants. The additional root and rhizosphere exploration enhances iron and nutrient content of uplifted water, promoting the generation of iron concretions (see Surficial processes affecting geomorphology section and the Soils chapter). As a result, habitats near Ida Fault have an extensive cover of soils containing iron concretions.

The granite-dominated western Yilgarn has few faults and shear zones. The most significant fault west of Ida Fault is the north-north-west trending Koolyanobbing shear zone, which is between 6 and 15 km wide and may be more than 650 km long (Libby et al. 1990). It stretches from the Yilgarn's southern boundary, constraining the western margin of Lake Johnston and

Koolyanobbing greenstone belts. The north-west trending faults truncate where the AFO starts, although there is evidence of structural variations within the AFO lithosphere related to the strike of Ida Fault (Sippl et al. 2017).

The EGST contains numerous faults and shear zones that align predominantly north-north-west to north-west and are conduits for preferential water flow and foci for weathering. Within valleys of the EGST, there are faults and geological contacts that focused erosion, influenced valley location and development prior to infilling and consequently resulted in topographic uplands (hills and ridges) on more competent rock sequences (Clarke 1994; De Broekert and Sandiford 2005).

Faults of the AFO generally strike north-east and concentrate along the junction where the Yilgarn truncates at the Cundeelee and Jerdacuttup faults (Clark 2004). An exception is where the Biranup, Fraser and Nornalup zones converge, where a prominent S-bend of the Fraser Fault diverts around the south-west extremity of the Fraser Zone. To the south-east, the Newman and Boonderoo shear zones separate the Fraser and Eastern Nornalup zones. The junction of these faults is the inferred extrusion of the southern Fraser Zone towards the south-west (Spaggiari et al. 2011).

Deep-Earth influences on topography

The survey area lies on a long-lived continental passive margin. The present topography has resulted, over time, from dynamic topographic adjustments, which warp the land surface, and which, in combination with erosion and sediment redistribution, expedites planation of the land surface, altering overburden pressure. Dynamic topography refers to elevation changes of the Earth's surface induced by mantle convection. It is positive over large-scale mantle upwellings and negative above subducted slabs (Greff-Lefftz et al. 2017; Hoggard et al. 2021). It results in elevation variation of the order of less than 1 km and has 3 distinct deformation modes resulting from stress regimes operating at 3 scales of areal influence: local (about 10–100 km), regional (about 100–1,000 km) and continental (about 1,000 km, or more) (Sandiford et al. 2009). In principle, topographic variation caused by variable mantle activity is a continuum that occurs over all scales (Flament et al. 2013), so continental-scale processes also influence topography at local and regional scales. Even so, continental-scale mantle processes are described last because mantle-driven topographic change is a critical component of relative sea level change, and the main driving force for generating the spatial geometries and timings of large-scale continental inundation through time (Müller et al. 2018). This concept fits well with the next section on paleotopography.

At local scale, Quaternary fault scarps are present and visible (Figure 4.4; Clark 2010; Clark et al. 2011). Faults are ruptures caused by intraplate stresses resulting from regional and continental mantle and tectonic processes (Clark et al. 2011). Fault scarps identified within and near the survey area are summarised in Table 4.1. Several of these have obvious geomorphic consequences at the local scale, redirecting creeklines, ponding water and forming wetlands. The most prominent in the survey area is the Lake Johnston scarp north of Kartukartunga (Peak Charles). This fault scarp runs north–south, has an east-side up/west-side down vertical displacement of several metres and has altered surface hydrology at several locations (Clark 2010).

Regional-scale lithospheric warping is caused by variable mantle circulation (upwelling and downwelling or drawdown) and differences in crustal buoyancy. 'Regional' mantle circulation varies due to subducted slab fragments affecting the temperature and density of the surrounding and overlying mantle. Surface topography alters laterally over time as tectonic plates migrate over underlying mantle, resulting in regional buoyancy variations (Gurnis and Müller 2003; Sandiford 2007; Heine et al. 2010).

Table 4.1: Fault scarps of the survey area and surrounds

Name	Length (km)	Strike (degrees from north)	Maximum scarp uplift (m)
71 Mile Rock scarp	23	169	7
Bulyeranging scarp[1]	39	7	3.75
Clives fantasy	17	204	6
Coondarrie scarp	23	175	2–3
Hyden north scarp	40	184	2.5
Hyden south scarp[2]	26	160	10
Iron Cap scarp	53	174	10
Koolyanobbing scarp	21	35	4–6
Lake Johnston scarp	37	13	7
Lort River scarp[3]	40	24	2.6
Moolyal scarp	35	176	2.3
Mt Holland east lineament	15	169	2.2
Norseman scarp	42	176	5
Parker Range scarp	28	5	3.5
Queen Victoria Springs scarp	21	12	10
Woodcutters camp scarp	24	136	3–5

1 Bulyeranging scarp is outside the survey area, north-west of Lake Campion Nature Reserve, between Nungarin and Lake Deborah.

2 Hyden south scarp is outside the survey area, in Dragon Rocks Nature Reserve, south of Hyden.

3 Lort River scarp is outside the survey area, in Fields Nature Reserve, east of Cascade.

Source: Adapted from Clark (2010)

Past marine inundation of the survey area's south-eastern flank is partially attributed to the presence of mantle drawdown now affecting the Australian-Antarctic Discordance, a tectonic feature with anomalously deep seafloor bathymetry south of the survey area and the Nullarbor (Gurnis and Müller 2003). Regional variation in crustal buoyancy results from differences in density between the Fraser Zone and surrounding siliceous basement of the Kepa Kurl Boolya geological province, inducing a large gravity anomaly. This causes the crust around Fraser Range to depress, inducing crustal flexure and local crustal stresses at the margins (Sippl et al. 2017).

Continental shelves and coastal zones of rifted passive margins are subject to mantle heat flux instability that generates elevation changes over time (Armitage et al. 2013; Hoggard et al. 2021). Old, dense oceanic mantle and crust south of the survey area have sagged under negative buoyancy, which also dragged down attached continental crust. This process formed the Ravensthorpe Ramp, whose hinge line runs along the survey area's southern margin and between lakes Cowan and Lefroy. This affected southern parts of the survey area by directing river systems south, which are presently etching northward by headward incision into the south-western survey area margins (Cope 1975; Clarke 1994; Beard 1999).

Since the Late Mesozoic, 4 continental-scale processes between the crust and mantle have had particular influence on dynamic topography within the survey area. First, the Australian and

Antarctic parts of Gondwana were located over the African mantle super-swell from the Jurassic to the Cretaceous (Harrington et al. 2019); this resulted in the elevation of Gondwana. Second, west-dipping subduction of the Pacific plate under eastern Gondwana during the Cretaceous forced a fragment of crust under the eastward-migrating Australian continent; this caused mantle downwelling that initially depressed the eastern part of the continent and then moved west under the continent's interior, causing subsidence and inundation there (Gurnis and Müller 2003). Third, Australia's redirection through the Cretaceous and Early Cenozoic, from easterly to northerly migration, caused protracted rifting between Australia and Antarctica. This altered mantle heat flow and structural controls, causing sedimentation in basins and localised uplift along the southern margin (Schofield and Totterdell 2008; Czarnota et al. 2013). Finally, Australia's northward motion and interaction with the Melanesian subduction realm has tilted the continent along a north-west–south-east axis, causing the northern margin to sink some 300 m relative to the south-west since the Eocene (Sandiford 2007; DiCaprio et al. 2011).

The lateral and vertical tectonic motions of the Australian continent through the Late Mesozoic and Cenozoic have been pivotal in the geomorphological evolution of the landscapes within the survey area. Furthermore, Australia's circum-continental passive margin, subdued topography and lack of major tectonic activity have preserved the geomorphic evidence of its tectonic heritage.

Paleotopography of southern Australia

Widespread Permian glaciation of the Western Australian shield planated much of the land surface and laid the foundation for subsequent topographic development (Mory et al. 2008).

During the Jurassic period, the Yilgarn Craton was a peneplain of low relative relief (Sircombe and Freeman 1999). Western Gondwana was located over the African mantle super-swell, which uplifted the entire landmass and preferentially elevated WA (Torsvik et al. 2014; Barham et al. 2018; Harrington et al. 2019) to form a broadly domed high plateau with a north-orientated central watershed, which is still present (Beard 1998).

Over the Late Jurassic to Early Cretaceous, a divergence rift zone developed between Australia and Antarctica parallel to the present south coast. The rift initiated from the west under the influence of a north-west to south-east extensional regime caused by Australia's eastward motion (Schofield and Totterdell 2008). Rivers orientated west and east drained the plateau and scoured channels through deep regolith and into Yilgarn basement (De Broekert and Sandiford 2005). The rivers had low gradients and the land was well vegetated (see Paleoclimate section in the Climate chapter) so the plateau was largely retained with only localised incision. Drainage of the western part of the survey area likely flowed west and south to the developing rift, forming canyons on the continental shelf (Von der Borch 1967; Beard 1999).

In contrast to the stable hinterland and southwards drainage of the Yilgarn Craton, a barrier range formed on the AFO basement as the rift propagated eastwards (Müller et al. 2018; Harrington et al. 2019). The AFO was actively eroding and had significant gradients that sloped east or south-eastward (Barham et al. 2018). This range restricted east-flowing drainage from the Yilgarn plateau to an exit located north of Fraser Range in the now occluded valley that contains Harris Lake (De Broekert and Sandiford 2005; Barham et al. 2018).

Thermal subsidence of the Bight Basin (south of the survey area) during the Early Cretaceous resulted in fluvial–lacustrine sedimentation derived from local sources including the AFO but having minimal input from the Yilgarn Craton (Barham et al. 2018). Sedimentation increased as thermal subsidence accelerated in the Middle Cretaceous. The increasing sedimentation was augmented by an increased supply from the rift margin of southern WA, which was uplifted during the Cretaceous (Harrington et al. 2019; Braz et al. 2021).

Despite a global sea level maximum at the end of the Cretaceous, sedimentation ceased in the Bight Basin because Australia's concurrent movement over a mantle upwelling caused widespread uplift. During this time, continental Australia became entirely exposed and was estimated to be 250 m higher than at present (Gurnis et al. 2000; DiCaprio et al. 2009). After this late Cretaceous exposure during the Eocene, Australia gradually subsided as it moved off the mantle upwelling and onto a mantle downwelling (DiCaprio et al. 2009), resulting in inundation of the Eucla and Bight basins by marine transgressions.

There is little evidence for denudation during the Cretaceous hiatus, despite prolonged exposure (Barham et al. 2018). Instead, erosion was restricted by a stable, humid climate with abundant vegetation and the gradually subsiding land surface. This resulted in deep regolith forming under a subdued plateau surface containing river systems that became occluded after being infilled with sandy fluvial sediments during the Eocene (Gurnis and Müller 2003; De Broekert and Sandiford 2005; DiCaprio et al. 2009).

Australia began its rapid northward drift after separating from Antarctica during the Eocene circa 44 Ma, and the Southern Ocean was formed. Thermal subsidence caused downwarping, which was accompanied by Eocene marine transgressions that extended onto the Yilgarn and AFO margins from the south and east. The Middle Eocene Tortachilla transgression extended into the Lefroy paleovalley and deposited high energy deltaic–estuarine sandy sediments (Clarke et al. 2003; De Broekert and Sandiford 2005). The Late Eocene Tuketja transgression inundated the Lefroy paleovalley with deeper waters than the Tortachilla transgression, resulting in low-energy, shallow marine (<40 m) waters in which spongolite was deposited (Clarke 1994; Gammon and James 2003; Hou et al. 2008). The transgressions also formed wave-cut platforms (Myers 1995). The spongolite now lies at 280 m above sea level (ASL) and the wave-cut platforms are now located at about 300 m ASL. These features indicate coastal erosion and concurrent deposition in deeper water have combined to planate surfaces, submerged during Eocene transgressions, to about the 300 m ASL contour. Terrestrial surfaces above about 300 m ASL remained exposed. These were already subdued but were further smoothed by weathering.

The Cenozoic northward motion of Australia into the Melanesian subduction realm and off the Antarctic dynamic high has subsided the entire continent. Australia rotated clockwise during the Miocene as it moved northward, colliding with Melanesian land masses in the north-east and experiencing drag from New Zealand in the east. Presently, north-eastern Australia has tilted down at least 300 m relative to the south-west of the continent. This tilting is evident in Eucla Basin gradients and paleoshorelines, and in river profiles around the continent's margins (Sandiford 2007; Hou et al. 2008; Czarnota et al. 2013). In addition to this general subsidence, DiCaprio et al. (2011) partly attributed the Miocene transgression, which affected the eastern margin of the survey area, to subsidence caused by the passage of Australia over a dynamic mantle low, consistent with a subducted slab remnant, now aligned with the Australian-Antarctic Discordance. The north-down tilt is progressive and current.

Eastern catchments of the survey area were initially incised from the direction of the Eucla Basin depocenter towards the west, forming the eastern etchplain of the survey area. Since the increase in south-west up-gradients, the headwaters have progressively migrated towards the south, in response to the increasing elevation from this direction. The cumulative effects of initial subsidence in the east and then increasing downward tilt from the north-north-east match the anticlockwise radial form of headwaters of the eastern part of the survey area.

Surficial processes affecting geomorphology

Erosion and deposition across the survey area are significantly affected by hydro-eolian, eolian and diagenetic cementation processes.

Hydro-eolian processes

The protracted geological stability of the landscape, arid climate and proximity to marine sources of advected salt result in a large accumulation of salt within the region's regolith. The low relief also facilitates the accumulation of groundwater, which has little opportunity to flush. Combined, these characteristics result in saline areas that express as playas and salt lakes with varying salt concentration in their water sources and sediments.

Wetting and drying cycles and seasonally variable winds contribute to sorting and redistributing sediments on bare lake beds. The sorting process (called swash) is also affected by the salinity regime because fresh water disperses clays to facilitate the physical sorting of sands during wet periods, whereas salty water flocculates clays, forming a protective film on the lake bed that limits sorting and eolian removal of lake bed sediments. Sand grains remaining on the lake bed after sorting by low-salinity water and subsequent drying are prone to removal by wind. Lake beds are sorted cyclically during dry periods. Since the strongest winds during dry periods are from the west, the sands are mainly deposited to the east of lakes. Fresh to brackish lakes (except for swamps that are vegetated and protected from erosion) and those with sandier parent material generate the largest sand sheets and lunettes. As this process progresses, the eastern side of lakes accumulates eolian sediments that originated from the western sector of lake bed and shore. In contrast, deflation of the western part of the lake collects subsequent rainwater, so swash and wind erosion processes become more pronounced towards the west of the lakes. This causes the lakes to erode in the direction of the prevailing winds, and the eolian deposits to extend downwind. Most lakes within the survey area have extensive sandy banks and sand sheets at their eastern margin and are eroding on their western margin. Often, this erosion etches into regolith and undercuts cemented layers, forming prominent breakaway scarps.

Gypsum deposits form similarly. However, the gypsum concentration process is different from the sand sorting process discussed above. Gypsum is a salt (hydrous calcium sulfate) that precipitates as crystals when hypersaline water evaporates from the beds of salt lakes. When all surface water has evaporated, strong winds can erode the precipitated gypsum crystals from the lake beds. The eroded gypsum crystals accumulate locally as rises and lunettes that form on the lake beds and on the downwind margins of salt lakes.

Eolian processes

Eolian landforms are mostly restricted to the arid north-eastern part of the survey area. Here, sandy sediments of the Canning and Officer basins have been reworked by wind into linear dunes orientated east-south-east to west-north-west, forming extensive dunefields. Linear dunes form in source-limited environments (Wasson and Hyde 1983). In these dunefields, the arid climate and the fire-prone hummock grassland provide opportunities for localised reworking, but their linear form and easterly orientation are stable. They formed and were most active during climatic dry periods during the Holocene (Bowler 1976).

Cementation processes

The latter stages of scarp development are well-established. A hard surface layer protects underlying erodible layers from raindrop erosion and headward incision. Once the hard layer is breached in part, the softer underlying layer is easily eroded. Thus, a scarp develops with the hard upper layer limiting the rate of erosion, but ultimately not preventing it.

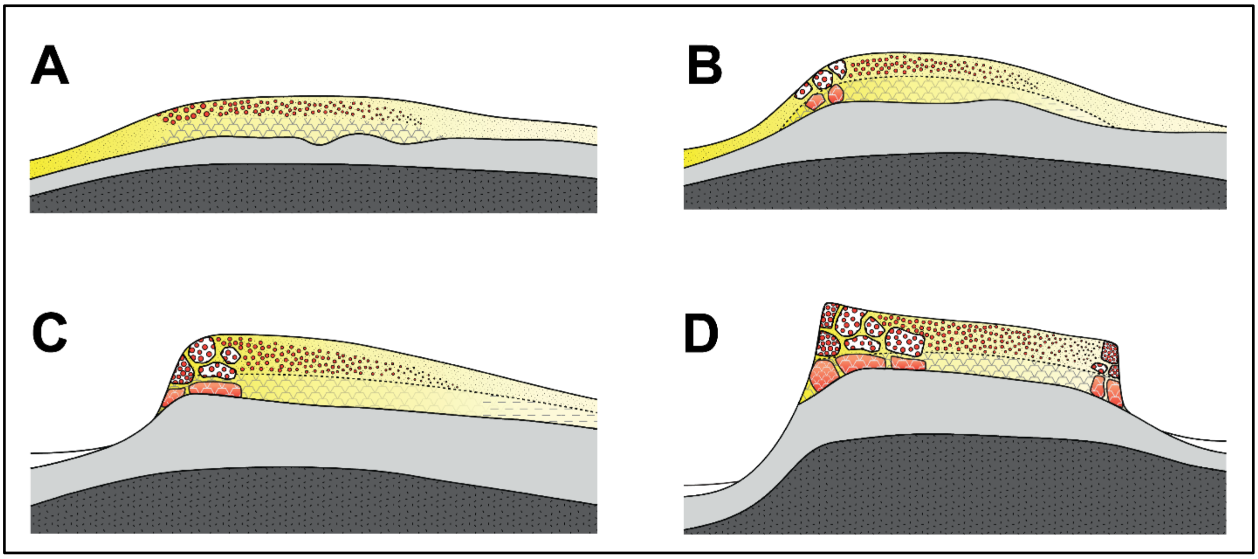
Breakaway scarp with an indurated upper layer above an erodible underlying layer

However, the process that creates iron-cemented layers remains the subject of considerable conjecture. Iron-enriched scarps are the most common hard layers in old landscapes of the survey area. They have long been considered products of tropical deep weathering and fluctuating watertables. An alternative, biogenic explanation – that describes how interactions between vegetation and soil microbiology form iron concretions in microporous niches within the soil profile – is presented in the Soil formation section in the Soils chapter. This biogenic model explains the formation of iron concretions without requiring extended tropical conditions, deep weathering or fluctuating watertables. The biogenic model is consistent with paleoclimate conditions described in the Climate chapter, and is supported by paleoclimate, palynological and geological evidence presented in Gammon and James (2003), Hou et al. (2008) and Chivas and Bird (1993). In the biogenic model, a deep regolith can develop after iron concretions have formed in surficial soil.

Verboom and Galloway (2000) proposed a cementation mechanism that is consistent with the biogenic model for iron concretions and explains the variety of cemented materials and geomorphic forms associated with scarp development. The mechanism that generates iron concretions – bacterial precipitation of iron chelated to organic compounds exuded by plants, symbiotic and free-living fungi, and soil microbes, as described in the Soils chapter – is also responsible for cementation of soil materials at developing scarps. The mechanism requires the presence of iron-manipulating bacteria in a soil matrix that has sufficient capillarity to preferentially concentrate soil water containing plant root exudates and chelated iron. The soil matrix near a scarp has a large surface area to volume ratio, compared to a land surface without the developing scarp face present. This additional surface area increases wicking (capillarity) to the developing scarp face. The extra wicking increases the concentration of chelated iron, which precipitates as microbes consume the organic ligand. As the iron precipitates, it cements the component soil matrix materials, whatever they may be. In this way, scarp faces are composed of a continuum of precursor soil profiles:

- abundant iron concretions (ironstone gravels) that subsequently cemented together
- iron concretions in a cemented sandy or loamy matrix
- iron-cemented subsoil clayey material.

Well-developed breakaway mesas consist of cemented materials that vary in iron concretion size and abundance from one part of the scarp to another (Figure 4.5).



Source: Adapted from Verboom and Galloway (2000)

Figure 4.5: Progressive development of iron-cemented scarps:
A) Gravelly ridge develops under the influence of iron-fixing soil microbes and vegetation that exude soluble carbon (principally proteaceous heath; see Soil formation section in the Soils chapter)
B) Gravels armour the surface and reduce erosion from raindrop impact in comparison to unarmoured proximal surfaces either side of the gravel ridge. These unarmoured surfaces erode more rapidly and expose the gravel ridge
C) As exposure increases, the biological gravel-forming soil processes start to operate on the bulk soil matrix at the ridge margins. As evaporation increases because of increased surface area, more iron precipitates and increases capillarity, which in turn increases the concentration of iron-organic ligand components in the soil solution, and positive feedback continues to cement the developing scarp
D) At the latter stages of scarp development, the biologically-rich soil zone is underlain by the pallid zone, which has a relative paucity of iron-precipitating bacteria and so cannot become indurated. This soft clay zone is erodible, allowing the overlying iron-cemented surficial soil to become undercut, thus forming the characteristic breakaway profile.

Physiography

The survey area is characterised as an extensive plateau to the west and etchplain of low relief to the east. Most of the area has deeply weathered regolith, infrequently punctuated by emergent outcrops and linear ranges of resistant rocks. The area drains via broad valleys that became progressively occluded by terrestrial sediments. The valleys are punctuated by playas and salt lakes that developed as the climate became more arid. Surficial eolian sediments, predominantly sandy, concentrate at the south-east extension of playas. Southern and eastern margins of the survey area comprise level to gently undulating marine sedimentary plains and wave ravinement surfaces (James et al. 1994; Zecchin et al. 2019) with sandy quartz and calcareous sediments locally reworked by eolian processes. The north-east margin of the survey area contains the south-western extremity of an extensive sandy desert comprising linear dunes formed from reworked Mesozoic sediments in a source-limited eolian environment (Wasson and Hyde 1983).

This survey revises the previous physiographic mapping of the area and has been correlated to the mapping of Tille (2006) and Pain et al. (2011). The hierarchical system of DPIRD's soil-landscape mapping is maintained, and new zone boundaries and physiographic descriptions have been added (see Methods chapter). The physiographic descriptions below focus on geomorphological characteristics; for soil-landscape zone summaries of soil and vegetation characteristics, refer to the Vegetation and habitat type ecology chapter. A correlation of hierarchical physiographic mapping of Tille (2006), Pain et al. (2011), and soil-landscape zones described during this survey are shown in Table 4.2.

Table 4.2: Comparison of hierarchical physiographic mapping systems with this survey

Physiographic units from the Australian Soil Resource Information System (ASRIS) (Pain et al. 2011)			WA soil-landscape units (Tille 2006)		WA soil-landscape zones (modified by this survey)
Division	**Province[1]**	**Region[1]**	**Region[1]**	**Province[1]**	**Zone**
Western Plateau	Yilgarn Plateau	Avon Plateau	Western	Avon	South-eastern Zone of Ancient Drainage
					Northern Zone of Ancient Drainage
		Southern Goldfields Plateau		Kalgoorlie[2]	Bimbijy Sandplains
					Mount Jackson Plains and Hills
					Youanmi South[3]
					Tay[3]
					Kambalda[4]
					Dundas[3]
		Leemans Sandplain		Murchison	Leemans Sandplain
					Salinaland plains
		Coonana-Ragged Plateau		Stirling[2]	Fraser Range[3]
					Nanambinia[5]
		Salmon Gums Plain			Salmon Gums Mallee
	Sandland	Great Victoria Desert Dunes	Sandy Desert	Great Victoria Desert[6]	Southern Great Victoria Desert
					Sydney Simpson
	Nullarbor Plain	Bunda Plateau	Central Southern	Nullarbor	Nyanga
					Gambanca

1 The hierarchical mapping of ASRIS and WA reverse naming conventions of province and region, despite being equivalent in scale.

2 Provinces of Tille (2006) that have been significantly revised during this survey.

3 Zone was newly described during this survey.

4 Zone was significantly revised during this survey.

5 Zone reallocated from Kalgoorlie Province to Stirling Province.

6 Great Victoria Desert Province was called Gunbarrel Province by Tille (2006) but has since been renamed to suit the naming convention of Pain et al. (2011).

Physiographic regions and provinces

The survey area is composed of 3 physiographic regions, which subdivide into 6 physiographic provinces, which subdivide into 17 soil-landscape zones. In order of decreasing geographic extent within the survey area, the provinces are Kalgoorlie, Stirling, Great Victoria Desert, Murchison, Avon and Nullarbor.

Most of the survey area lies within the Western Region, which is described by Tille (2006) as undulating plateaus comprising plains, hills and ranges, and coastal plains, on the Precambrian shield of the Archean Yilgarn and Pilbara cratons, the Proterozoic Capricorn and Albany-Fraser orogens, and the Phanerozoic Carnarvon, Perth and Bremer basins. The 4 provinces of the Western Region occupy most of the survey area. They are the predominant Kalgoorlie and Stirling provinces, which occupy the survey area's centre and south respectively, and the marginal Avon and Murchison provinces, in the south-west and north, respectively (Figure 4.6).

The eastern extremity of the survey area lies within the Sandy Desert Region in the north-east and the Central Southern Region in the east. The Sandy Desert Region is described as sandplains and dunes on sedimentary rocks of the Canning and Officer Basins (Tille 2006). The Central Southern Region is described as limestone and calcrete plains on marine limestone of the Eucla Basin (Tille 2006).

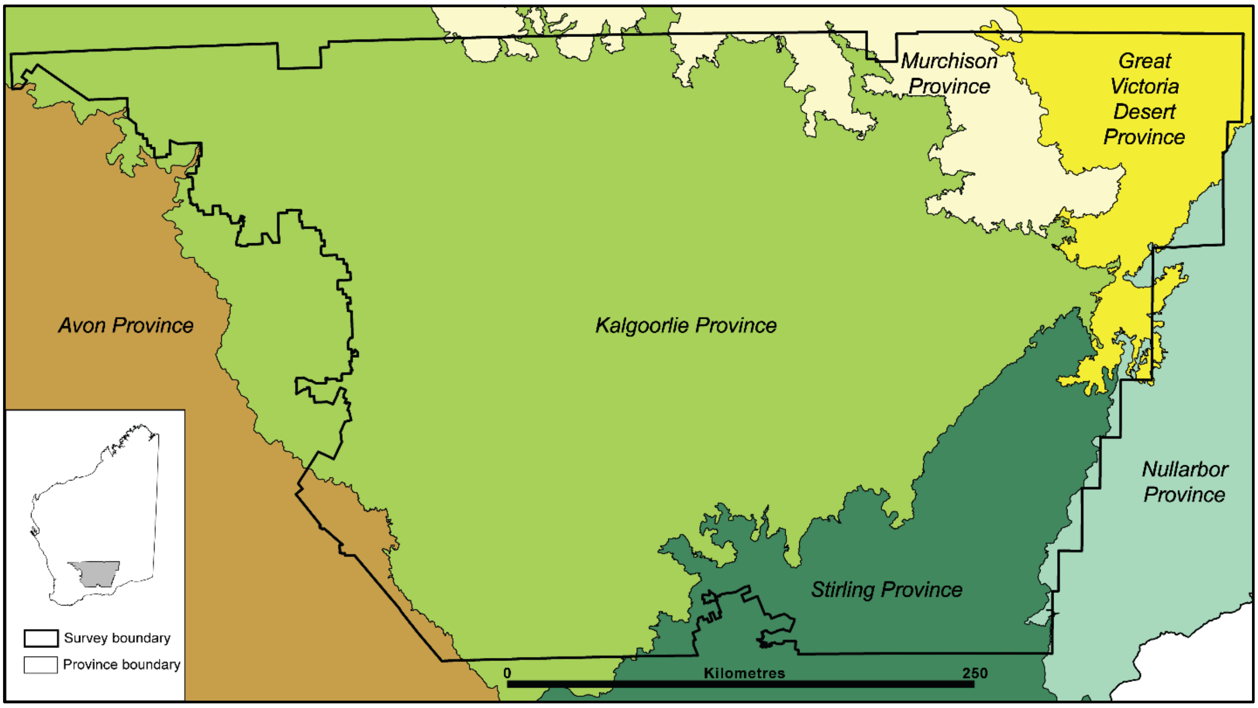
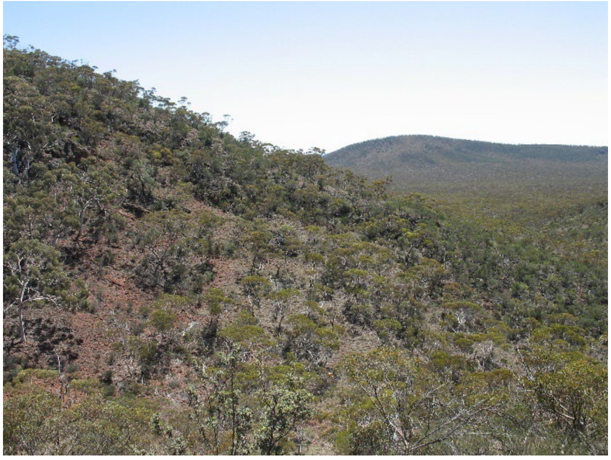


Figure 4.6: Soil-landscape provinces in the survey area

Kalgoorlie Province

The Kalgoorlie Province comprises undulating plains interspersed with sandplains, hills and salt lakes on Yilgarn Craton granites and greenstones (Tille 2006). It is generally deeply weathered with gently undulating and subdued relief, except where the regolith has become indurated to form mesas and breakaways. Some parts are less weathered, forming hills and low hills of resistant rock that emerge from the surrounding plains. In the survey area, the most prominent hills form from BIF, a grand example of which is Bungalbin (681 m ASL; Helena and Aurora ranges). Elsewhere, granite inselbergs and domes, such as Wallaroo (537 m ASL), Woolgangie (445 m ASL) and Queen Victoria (475 m ASL) rocks, form notable low hills, and metabasalt forms prominent hills, such as Jaurdi Hill (570 m ASL) and Mount Burges (554 m ASL) north of Coolgardie.


View from Bungalbin (Aurora Range)


View from Emu Hill overlooking Mt Burges

The Kalgoorlie Province contains the Jurassic continental divide (Beard 1998). An in situ sandplain overlying deeply weathered granite lies west of the continental divide and drains to the Swan-Avon catchment and Indian Ocean. This sandplain forms the eastern-most part of the Swan-Avon catchment and has very subdued gradients. In contrast, the undulating etchplain that lies east of the continental divide has steeper gradients and more active erosion than the sandplain. This etchplain drains inland, eastward to the Nullarbor Province.

Stirling Province

The Stirling Province is composed of gently undulating plains on a basement of AFO rocks and minor Yilgarn Craton granites, overlain by Bremer and Eucla basin marine sediments. Shore margins and shallow offshore sediments were planated by waves and currents during marine transgressions. The eroded sediments were deposited locally in deeper waters. This resulted in a subdued land surface after the seas receded.

Isolated emergent hills persist where resistant rocks formed islands during marine transgression phases. In the survey area, these resistant rocks include syenite of Kartukartunga (peaks Charles and Eleanora), metagabbro of the Fraser Range Zone, occasional granite inselbergs and rare Proterozoic quartzite metasediments of the Arid Basin. Elsewhere (outside the survey area), metamorphosed sediments of the Stirling, Barren and Ragged ranges and the Ravensthorpe greenstones all form prominent hills. Most of the Stirling Province has drainage that incises the landscape from the coast and flows south to the Southern Ocean, but within the survey area, most drainage of the upper catchments is very sluggish and drainage incision is yet to significantly affect the landscape. As a result, relief is generally very subdued.

Great Victoria Desert Province

The north-east corner of the survey area lies within the Great Victoria Desert Province (and Sandy Desert Region) of Tille (2006) and is described as sandplains and dunes interspersed with undulating plains and uplands on sedimentary rocks of the Canning, Gunbarrel and Officer basins. Tille (2006) named this the Gunbarrel Province, but it was subsequently renamed as the Great Victoria Desert Province to correspond with the naming convention of Pain et al. (2011).

Murchison Province

The Murchison Province has a very gently undulating surface of sandplains and hardpan wash plains underlain by granite and greenstone rocks mostly of the EGST. Within the survey area, all Murchison catchments drain via salt lake chains to Ponton Creek and eventually Lake Boonderoo in the Nullarbor Province, akin to eastern catchments of Kalgoorlie Province. These catchments are notably structured by rocky interfluves of granite and ridges of metamorphic rocks.

Avon Province

The Avon Province has a gently undulating surface of sandplains and ferruginous divides on Yilgarn Craton granites and gneisses, and limited areas of metasedimentary and metavolcanic rocks, and minor dolerite dykes. Most interfluves are deeply weathered although they contain lesser areas of stripped granitic and colluvial slopes that wane to broad alluvial valleys containing salt lake chains. The Avon Province has sluggish drainage that mostly flows west to the Swan River and discharges into the Indian Ocean, although the south-easterly portion of the survey area has been captured by south-flowing rivers that discharge to the Southern Ocean via the Stirling Province.

Nullarbor Province

The eastern margin of the survey area encroaches on the Nullarbor Province (and Central Southern Region) of Tille (2006) and is described as 'limestone and calcrete plains on marine limestone of the Eucla Basin'.

Soil-landscape zones

Each of the physiographic regions and provinces is subdivided into soil-landscape zones (Figure 4.7), which are delineated on geomorphic characteristics, particularly relief, thereby reflecting broad erosional and depositional patterns and landscape maturity. In describing the soil-landscape zones, they are grouped by the province they reside within. Provinces are ordered by geographic extent within the survey area. Then zones are listed within each province according to their geological, geomorphological and spatial relationships with neighbouring zones, as described in the Vegetation and habitat type ecology chapter.

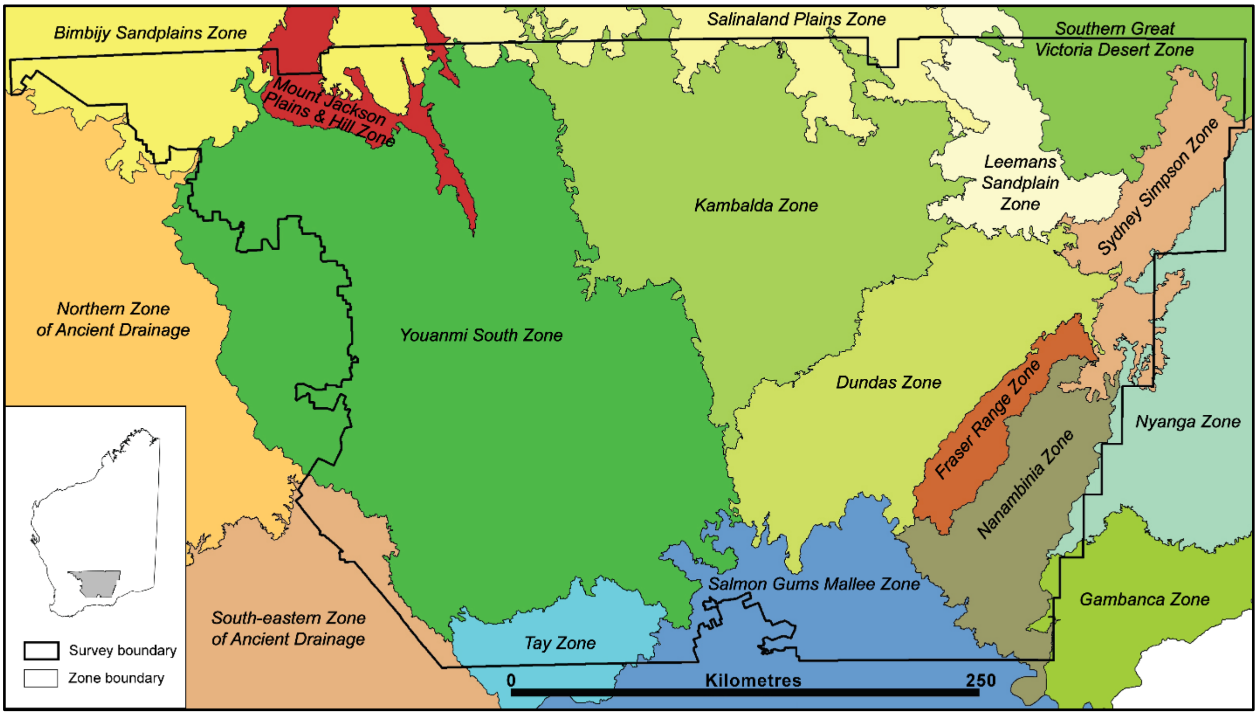


Figure 4.7: Soil-landscape zones of the survey area

Some soil-landscape zones are described by Tille (2006) and DPIRD (2021) and these descriptions are retained where they remain accurate. Where this survey revealed additional insights, these have augmented previous descriptions. Some soil-landscape zones are described for the first time because they were newly identified or significantly modified during this survey. These descriptions rely on insights developed during field investigations and from literature describing geology and geomorphology. Several of the zones previously identified have only been cursorily described because the reconnaissance survey generated insufficient additional knowledge. Summary descriptions are provided in Volume 2, Appendix B.

Zones of Kalgoorlie Province

Youanmi South Zone

This zone is described for the first time. It amalgamates the Southern Cross and Norseman zones of Tille (2006) to recognise the distinct geology of the southern part of Youanmi Terrane as one zone – the Youanmi South Zone. This amalgamation also realigns the zone boundaries between Youanmi South to the east, and South-eastern Zone of Ancient Drainage and Northern Zone of Ancient Drainage to the west, and thus separates the Youanmi Terrane from the South West Terrane. The eastern boundary of Youanmi South Zone is realigned to match the location of Ida Fault, which delineates the change in geology from the Youanmi Terrane, west of Ida Fault, to the Eastern Goldfields Super Terrane, east of Ida Fault.

The Youanmi South Zone occupies the western third of the survey area and comprises a gently undulating in situ sandplain plateau derived from Yilgarn Craton granitoid rocks. It has low relief at high elevation, relative to the dissected zones that surround it. The sandplain occurs on deep regolith comprising ferruginous gravels and duricrust that commonly overlie mottled zones and saprolite. Scarps (breakaways) of duricrust and ferricrete commonly rim the sandplain at its margins. The sandplain is dominated by deep sand in the north. Ironstone gravelly soils increase in prevalence towards the central and southern parts before yielding to gravelly duplex soils in the far south of the plateau. Protruding above the general elevation are granite inselbergs (monadnocks) such as Wallaroo Rock at about 530 m ASL, and linear ranges of low greenstone hills that are generally orientated north–south. The greenstone hills are locally abundant along the western margin of the zone and in the vicinity of Lake Johnston.

The sandplain straddles the central watershed (Beard 1998), a north–south continental divide with a maximum elevation within the survey area of about 480 m ASL. The watershed divides the plateau into 2 parts, one being the valleys whose now sluggish drainage flows west to the Indian Ocean, and the second being those that flow east towards the Eucla Basin and Southern Ocean. Sandplain surrounding this watershed is relatively unaffected by headward incision from drainage systems that align north–south. These drainage systems have broad valleys that are sluggish and occluded with unconnected playas that become progressively more saline down the catchment. The lowest playa (salt) lakes lie at about 330 m ASL. Playas of the upper catchment have lower salinity and extensive windblown sand sheets that extend east-south-east. The large Lake Deborah salt lake system aligns with a major lineament that trends south-west along the Yilgarn River towards the Yenyenning Lakes (Salama 1994).

The extremities of the sandplain west and east are bounded by distinct breakaways. In the west, deeply weathered landforms are partially etched by tributary drainage of major valleys that feed into Lake Deborah. Headwaters often incorporate the ferruginous Euchre land system. In places, examples of the Euchre system have been affected by multiple episodes of erosion that have removed surficial materials but retained a veneer of weathered, nutrient-poor regolith. This regolith acts as parent material for the next phase of soil development. From this regolith material, plants and root microbes draw the nutrients needed for physiological function. The biota concentrates these nutrients in near-surface soil horizons by biochemical processes, further depleting the regolith below. Each erosive sequence strips the iron and nutrient enriched surface and depletes the total pool of iron and other nutrients available to the ecosystem. Consequently, land surfaces that have undergone several such sequences have progressively less iron available to form ferruginous concretions (see Soil formation section in the Soils chapter) and breakaway scarps. As a result, the soil becomes less fertile, gravels contain less iron and breakaways are less prominent. Ferruginous surfaces less affected by erosion retain prominent breakaways and thick gravel horizons, but these features are often diminished in the Euchre system because repeated erosional events decrease the iron concentration.

In contrast, the eastern sandplain margin has robust and prominent ferruginous breakaways of the Latimore and Illaara land systems that have abundant ironstone concretions. These breakaways preferentially form along faults and shear zones where iron-rich substrates are present and are prominent along Ida Fault. They do not show evidence of multiple stripping events and headwaters of the east-flowing drainage have not etched beyond Ida Fault.

The south-east portion of the Youanmi South Zone has been partly etched at the headwaters of the Lake Johnston catchment, which drains to Lake Lefroy. This area, along with the western margin of the zone, has greenstone outcrops, colluvial slopes and salt lakes of the Johnston drainage system. Extensive calcareous silty deposits have blown from the lake beds and are deposited at the south-eastern margins.

Mount Jackson Plains and Hills Zone

The Mount Jackson Plains and Hills Zone comprises prominent steep hills, steep to rolling rises with colluvial aprons, and undulating plains punctuated by active drainage channels formed on thick metasedimentary greenstone sequences that contain significant proportions of BIF. It occurs between Koolyanobbing, Mount Jackson, Ularring and Mount Dimer. Elevation of the plains is between 420 and 450 m and the highest peak, Bungalbin Hill, crests at 615 m ASL. The zone represents major greenstone outcrops that resist erosion largely because of the presence of thick sequences of BIF. The greenstone hills are significantly enriched with secondary iron accumulations, forming ironstone concretions (see Soils chapter). The hills and ranges grade laterally into colluvial aprons, footslopes and undulating plains mantled by ironstone concretions or lithic rock fragments, which prevent erosion. Rocky surfaces generate significant run-off that flows into short, active stream channels and occasional swamps. Gently undulating plains have in situ sandplain or hardpan plains derived from granite but are minor in extent.

Bimbijy Sandplains Zone

This zone was described by Tille (2006), which is slightly amended here for consistency, while retaining the original intent and detail. Most of this zone lies north of the survey boundary, so only a reconnaissance survey was undertaken along the zone's southern margin.

The Bimbijy Sandplains Zone comprises sandplains and some salt lakes and mesas on granitic rocks of the Yilgarn Craton between Lake Moore, Lake Barlee and Mount Jackson.

Tay Zone

The Tay Zone is a very gently undulating peneplain of extremely subdued relief with internal occluded drainage on deeply weathered granitic basement with some Eocene marine sediments that are mostly calcareous. It occurs between North Cascade, Lake King and Forrestania. This zone represents the remnant headwaters of the east-flowing Cowan paleovalley. It lies south of Youanmi South Zone and separates the inland drainage of Youanmi South from the south-flowing coastal rivers of the Ravensthorpe Ramp (Beard 1999).

Relief is extremely subdued: catchment headwaters of the north and south have average gradients of 0.5% and 0.3%, respectively. Flow of the major Tay paleovalley has reversed, most likely due to regional uplift to the east. It originally flowed to Lake Dundas but now is entirely internal with Lake Tay, at about 230 m ASL, lying some 15 m below the level of Lake Dundas. Exceptions to the low relief are the 2 prominent inselbergs of Kartukartunga – Peak Charles has an elevation of 650 m, and Peak Eleanora rises to 485 m. These 2 inselbergs are the only significant outcrops of rock. Elsewhere, the zone is deeply weathered and retains fine sandy surfaces within only very minor outcrops. These in situ sandplains are subjected to minor eolian reworking immediately after fires that regularly perturb the extant mallee woodland. The valleys are occluded with saline playas that have extensive windblown sandy deposits downwind of their eastern margins. Large playas have significant gypsum lunettes overlying their beds and at their eastern shores.

Kambalda Zone

This zone was first described by Tille (2006) and was extensively revised during this survey. The southern extent of the revised zone retracts northwards from Tille's original boundary and Tille's southern and eastern parts are reassigned to the Dundas Zone.

The Kambalda Zone lies immediately east of Youanmi South Zone, in the north-central part of the survey area. The Kambalda and Youanmi South zones are separated by Ida Fault. At the western margin of the Kambalda Zone over the Ida Fault, ironstone gravelly surfaces are dominant and become indurated to form prominent breakaways. These features are effective barriers to erosion and facilitate development of deep regolith.

Most of this zone comprises an extensive etchplain whose drainage systems have variably exposed the Archean basement of greenstone, granite and metasedimentary rocks. Interfluves of the etchplain generally reflect the underlying north-north-west geological structure, and resistant hills and strike ridges of BIF stand proud of the general land surface. Granite is extensive in the north-eastern parts. In situ sandplains have developed on the granite, but low stony rises of granite are exposed where erosion has occurred. Hills and divides yield to extensive sheetwash plains and then alluvial valleys. The plains and valleys are filled with detritus from the surrounding uplands and underlying rock. Greenstone weathers to clay and is erodible, so interfluves have rocky crests with extensive sheetwash plains and calcareous clay-filled valleys. In contrast, granitic terrain has rounded uplands with outcrops surrounded by extensive gently undulating sandplain yielding to loamy sheetwash plains on lower slopes. The south-western margin of this zone approximates the Eocene shoreline during the transgression peak. In this area, parts that were inundated have subdued relief. In contrast, their terrestrial flanks that avoided inundation contain rolling rises and low hills. Both landforms are enriched in calcareous soil minerals originating mostly from meteoric accessions derived from marine sediments (Dart et al. 2007). Inland, the proportion of calcium carbonate in soil that originates from bedrock increases, but sedimentary carbonates remain the dominant source (Dart et al. 2007). Calcium ions are drawn from deep regolith and concentrated in surface soils by hydraulic redistribution performed by large trees with deep roots (mostly *Eucalyptus* and *Casuarina* species). The calcium ions are released from plants and fungi as calcium oxalate, which is converted to calcium carbonate by specific bacteria, forming calcium carbonate gravels and calcrete hardpans in prior soil profiles and as calcareous shallow loam soils.

The etchplain of the Kambalda Zone has eroded from the east by sequential episodes that deposit sediments locally because of low gradients, local knick-points that set the base level at a subcatchment scale, and intermittent water flow. At a regional-scale, eastern parts of the etchplain, which eroded first, have subsequently formed new soil and regolith. These areas now have significant regolith, minor exposed bedrock and large colluvial mantles. In contrast, the central part of the etchplain is currently eroding and has more exposed bedrock. Here, headwaters of the central etchplain are variably stripping the regolith, exposing bedrock in places, while extensive gravelly mantles are retained where etching is less active.

A consequence of this stepwise regional erosion is that younger subcatchments – whose headwaters originate in unweathered rocky terrain and so generate fresh run-off – form fresh and brackish ephemeral drainage tracts that locally terminate in swamps and lakes. Conversely, older subcatchments – those whose headwaters originate in deeply weathered terrain with significant salt stores – form salt lake chains.

Water from both ‘forms’ of subcatchment contribute to the major valleys, which are occupied by numerous saline playas and the major lakes Yindarlgooda, Rebecca (both at about 340 m ASL), and Lefroy (at about 290 m ASL). Calcareous sand sheets have formed from windblown deposits downwind of the south-eastern margins of salt lakes and saline playas. Hydraulic redistribution, principally by large trees including eucalypts and casuarinas, concentrates calcareous material in near-surface soil, forming carbonate gravels, calcrete pavements and hardpans.

Dundas Zone

The Dundas Zone occupies low-lying and generally subdued plains between the Fraser Range Zone to the east, the Spinifex Range to the north, and the un-named range incorporating Cowan Hill between lakes Lefroy and Cowan to the west. The zone represents an extensive wave ravinement platform on mixed Archean and AFO crystalline basement and has an extensive but thin sedimentary surface of calcareous fine sand, occasional spongolite outcrops and uncommon low, domed outcrops of crystalline basement rocks. Salt lake chains occupy poorly defined, sluggish valleys and have extensive windblown sandy deposits blanketing surfaces beyond their south-east margin.

Despite subdued surface topography, the Dundas Zone is not deeply weathered compared to zones that remained subaerial over the Cenozoic. This feature is attributed to extensive erosion in the wave energy zone of the very shallow marine environment. Paleogeographic features that support development of an extensive ravinement surface (Zecchin et al. 2019) are:

- very shallow marine environment (Gammon et al. 2000), resulting in significant wave energy
- very low terrigenous sediment supply due to low terrestrial relief, thick vegetative cover and low run-off regime
- the forming of the Tasman seaway (Barker and Thomas 2004) that resulted in open ocean conditions and a high energy marine environment (Jones 1990)
- the high latitude location of the survey area during transgressions in the Eocene (located 50°–60° south) and the Miocene (located 40°+ south), which resulted in significant storms that generated wave energy and seabed erosion.

The Dundas Zone is a mosaic of very subdued granite and gneiss domes surrounded by fine calcareous sandy sediments. The southern margin is defined by an indistinct and extremely subdued surface ‘catchment divide’ that nominally separates the northward directed salt lake chains from those whose general gradient is south. This line approximates the Ravensthorpe Ramp but is unlikely to separate groundwater systems.

Drainage is likely subterraneous – southwards via Lake Cowan and Lake Dundas and northwards through the Harris Lake paleodrainage, east of Lake Lefroy. From south-west to north-east, extensive lake beds become smaller connected lakes and then isolated playas. Surface drainage is evident only around the Fraser Range Zone, where it dissipates into Miocene calcareous marine sediments of the Sydney Simpson Zone. The broad valleys are occluded and host playas with extensive sand sheets at their eastern margins. Gypsum lunettes commonly occur on playa surfaces and proximal to their eastern shores.

Zones of Stirling Province

Salmon Gums Mallee Zone

This zone was described by Tille (2006). The original description is augmented with insights gained from several traverses during this survey, but there is limited modification because more than half the zone lies south of the survey area.

The Salmon Gums Mallee Zone comprises flat to gently undulating pediplains, relict marine plains and undulating plains with some salt lakes on crystalline and weathered Proterozoic granite and gneiss of the Northern Foreland of the AFO, Eocene marine sediments and minor alluvium.

This zone lies on the Ravensthorpe Ramp and has a gentle downwards tilt to the south. The north has low relative relief because Cenozoic transgressions planated rises and filled depressions with sediments. The south has low relief because it forms a relict marine plain, infilled with fine sandy and calcareous marine sediments. Drainage is indistinct across most of the zone, mostly expressed as isolated salt lakes in closed depressions. These become more common further south and within the broad Dundas paleovalley. Headward incision of south-flowing rivers has partially etched the southern margins of the Salmon Gums Mallee Zone, south of the survey boundary.

The highest broad rises generally have little or no marine sedimentary overburden and soils are formed on granite and gneiss. Where these landforms are vegetated by allocasuarina thicket, ironstone gravelly soils have developed and regolith is deeper. Where these landforms are vegetated by eucalypt woodland, red loamy and clayey soils have developed.

The lower plains of the north and most of the south of the Salmon Gums Mallee Zone forms a relict marine plain, infilled with sandy, calcareous marine sediments. Soils are fine sandy duplexes with calcareous clayey subsoil, vegetated by low mallee woodland.

Fraser Range Zone

This zone is new and not previously recognised. It has been assigned zone status because of its unique geological characteristics, local relief and landforms, soils and vegetation.

The Fraser Range Zone comprises steep to rolling hills and rolling to undulating rises with narrow valleys in the south, and rolling to undulating rises and undulating pediments in the north, on metagabbroic rocks of the AFO. It includes Southern Hills station and the upland landforms south of Zanthus siding (located on the Trans-Australian Railway).

Elevation of the southern portion ranges from about 250 to 540 m ASL, and averages between 350 and 420 m ASL. These hilly central and southern parts are elevated above the Eocene marine highstand and show no evidence of marine planation. Crests and upper slopes have skeletal soils that become deeper and more diverse on the lower colluvial slopes and in the valleys.

The central and northern parts are generally more subdued, ranging from 250 to 350 m ASL and 220 to 300 m ASL, respectively. The central part has rolling rises and pediments with shallow soil formed on gabbro and some calcareous gravels and calcrete soils over rock on the lower plains. The planated northern part has low relative relief and represents a marine erosion surface. It has shallow soils over rock with prominent jointing patterns that have calcrete platforms on them.

Nanambinia Zone

This zone was previously assigned to the Kalgoorlie Province as described by Tille (2006). Here, it is reassigned to the Stirling Province because it overlies AFO basement. The zone lies almost entirely within the survey area but because the zone is outside pastoral leases, its original description is augmented by limited reconnaissance conducted during this survey.

The Nanambinia Zone comprises gently undulating plains, sand sheets and pediplains with minor playa chains on planated granite and gneiss of the AFO, overlain by shallow deposits of Eocene and Miocene calcareous sandy sediments. It lies between the Fraser Range and Balladonia Roadhouse (Eyre Highway) in the Dundas Nature Reserve, and elevation ranges from 140 to 320 m ASL. The zone was subjected to marine transgressions during the Eocene and Miocene. It lay at the shoreward margin of Fraser Range, so was repeatedly subject to very shallow marine conditions and a high energy, erosional environment that planated the crystalline basement. Under these conditions a planar surface developed. It has low rises of granite outcrops interspersed with depressions containing shallow deposits of sandy and calcareous sediments. Outcrops and soil are interspersed with small playas that are mostly underlain by competent rock without deep regolith. This contrasts with the adjoining zones of the Nullarbor Province, which are largely devoid of playas.

Zones of Great Victoria Desert Province

Southern Great Victoria Desert Zone

This zone is based on the Main Dunefield within the Great Victoria Desert Dunefield Section (Jennings and Mabbutt 1977) and was also described by Tille (2006). The original intent and detail are retained here because most of this zone lies north of the survey area and so was only subject to limited reconnaissance.

The Southern Great Victoria Desert Zone comprises sandplains and linear dunes with infrequent gravelly plains and calcrete plains on sedimentary rocks of the Gunbarrel (and underlying Officer) Basin and the southern extent of the Canning Basin. The zone lies between Lake Minigwal and the South Australian border in the southern part of the arid interior at the south-western margin of the Great Victoria Desert Province.

This zone represents an extensive sandplain reworked by eolian activity into linear east–west trending sand dunes of Holocene age (Bowler 1976), which are up to 6 km long and 15 m high. The dunes are formed from local redistribution of regolith derived from Patterson Formation sandstone in the northern sequence, and sandy marine sediments in the eastern sequence. Occasional playas with gypsum lunettes at their eastern margins are present in the south.

Sydney Simpson Zone

This zone was described by Tille (2006). His original description is augmented by limited traverses and inventory sites undertaken during this survey.

The Sydney Simpson Zone comprises gently undulating plains, gently undulating pediplains and relict marine plains, and some salt lakes. It overlies crystalline and weathered Northern Foreland granite and gneiss and other Proterozoic rocks of the Albany-Fraser Orogen, Permian sandstone and tillite of the Gunbarrel Basin, Eocene marine sediments of the Eucla Basin, and Quaternary alluvium. It occurs between Rason Lake, Harris Lake, and the Zanthus and Kitchener sidings (Trans-Australian Railway).

This zone is a complex interzone allocated to the Great Victoria Desert Province in the Sandy Desert Region, but it has a relationship to both the Stirling and Great Victoria Desert provinces. It has been subject to erosion by wave ravinement during Cenozoic transgressions and probably represents the nearshore wave zone of the era. A veneer of shallow marine sediments forms a sand sheet that covers parts of the Sydney Simpson Zone, in parts reworked by eolian processes. Elevation ranges from 200 to 300 m ASL. The landforms are comparable to those of the Salmon Gums Mallee Zone, both being affected by marine erosion. However, the Sydney

Simpson Zone contains Permian, Eocene and Miocene sandy deposits whereas the southern Salmon Gums Mallee Zone contains only Eocene siltstone.

Zones of Murchison Province

Salinaland Plains Zone

This zone was described by Tille (2006) and is slightly amended here. However, the original intent and detail is retained because most of this zone lies north of the survey boundary.

The Salinaland Plains Zone comprises sandplains interspersed with hardpan wash plains and some mesas, stony plains and salt lakes, on granitic rocks and some greenstone of the Yilgarn Craton. It occurs in the northern Goldfields from lakes Barlee and Ballard to Wiluna and Laverton.

Leemans Sandplain Zone

This zone was described by Tille (2006) and Pain et al. (2011). These descriptions are augmented by this survey but are tenuous because only its southern portions were investigated by this survey.

The Leemans Sandplain Zone occupies an undulating and deeply weathered, partially etched sandplain on granite and greenstone crystalline rocks of the Yilgarn Craton (EGST), in the south-western arid interior between lakes Wells and Minigwal (east of Laverton). Extensive in situ sandplain remnants on granite are flanked by partially stripped regolith surfaces of hardpan wash plains, gravel plains and mesas. This zone has broad saline valleys containing numerous small and medium salt lakes. Across most of the zone the valleys are occluded. However, in the survey area, valleys have been weakly incised by Ponton Creek and the resulting gradients have been sufficient to prevent playas forming. In contrast, areas north of the survey area are not incised by Ponton Creek and have extensive salt lake chains.

Zones of Avon Province

South-eastern Zone of Ancient Drainage

This zone occupies the far western margin of the survey area and is described in soil-landscape surveys of the agricultural areas.

The South-eastern Zone of Ancient Drainage comprises gently undulating terrain interspersed with some salt lake chains and some areas of prominent granite outcrops, on deep regolith and alluvium over granitic rocks of the Yilgarn Craton. It occurs in the southern wheatbelt between Kondinin, Lake Grace, Gnowangerup, Frank Hann National Park and Mount Holland.

Northern Zone of Ancient Drainage

This zone barely imposes on the western margin of the survey area and is described in soil-landscape surveys of the agricultural areas.

The Northern Zone of Ancient Drainage comprises gently undulating terrain interspersed with some sandplains and salt lakes chains, on deep regolith and alluvium over granitic rocks of the Yilgarn Craton. It occurs in the eastern wheatbelt between Quairading, Bullfinch, Bonnie Rock, Lake Moore, Carnamah and Wongan Hills.

Zones of Nullarbor Province

Nyanga Zone

This zone was described by Tille (2006) and is slightly amended here for consistency. However, the original intent and detail is retained because most of this zone lies east of the survey area.

The Nyanga Zone comprises an extensive level marine plain on Miocene limestone (and occasional Eocene limestone) of the Eucla Basin and has silty and loamy soils containing pedogenic calcrete. It occurs in an arc from Balladonia (Eyre Highway) northwards along the western edge of the Nullarbor Province.

Gambanca Zone

This zone was described by Tille (2006). The original intent and detail are retained because most of this zone lies east of the survey area.

The Gambanca Zone comprises level and gently undulating marine plains on Eocene and Miocene limestones of the Eucla Basin and has silty and loamy soils containing pedogenic calcrete, interspersed with protruding inliers of Proterozoic granite of the AFO. It occurs between the Parmango Road–Balladonia Track, the Eyre Highway and the Cocklebiddy Roadhouse in the south-western Nullarbor.

References

Angerer T, Kerrich R and Hagemann SG (2013) ‘Geochemistry of a komatiitic, boninitic and tholeiitic basalt association in the Mesoarchean Koolyanobbing greenstone belt, Southern Cross Domain, Yilgarn Craton: Implications for mantle sources and geodynamic setting of banded iron formation’, *Precambrian Research*, 224:110–128.

Armitage J, Jaupart C, Fourel L and Allen P (2013) ‘The instability of continental passive margins and its effect on continental topography and heat flow’, *Journal of Geophysical Research*, 118:1817–1836.

Barham M, Reynolds S, Kirkland CL, O’Leary MJ, Evans NJ, Allen HJ, Haines PW, Hocking RM and McDonald BJ (2018) ‘Sediment routing and basin evolution in Proterozoic to Mesozoic east Gondwana: A case study from southern Australia’, *Gondwana Research*, 58:122–140, doi:10.1016/j.gr.2018.03.006.

Barker PF and Thomas E (2004) ‘Origin, signature and palaeoclimatic influence of the Antarctic Circumpolar Current’, *Earth-Science Reviews,* 66:143–162.

Barley ME, Brown SJA, Krapež B and Kositcin N (2008) ‘Physical volcanology and geochemistry of a Late Archaean volcanic arc: Kurnalpi and Gindalbie Terranes, Eastern Goldfields Superterrane, Western Australia’, *Precambrian Research*, 161:53–76.

Beard JS (1998) ‘Position and developmental history of the central watershed of the Western Shield, Western Australia’, *Journal of the Royal Society of Western Australia*, 81:157–164.

Beard JS (1999) ‘Evolution of the river systems of the south-west drainage division, Western Australia’, *Journal of the Royal Society of Western Australia*, 82:147–164.

Bowler JM (1976) ‘Aridity in Australia: Age, origins and expression in aeolian landforms and sediments’, *Earth-Science Reviews*, 12:279–310.

Braz C, Zahirovic S, Salles T, Flament N, Harrington L and Müller RD (2021) ‘Modelling the role of dynamic topography and eustasy in the evolution of the Great Artesian Basin’, *Basin Research*, 3300:1–28.

Brett JW (2017) *40 m magnetic merged grid of Western Australia 2017 version 1,* Geological Survey of Western Australia, Perth.

Brett JW (2018) *80 m radiometric merged grids of Western Australia,* Geological Survey of Western Australia, Perth.

Brett JW (2019) *400 m Bouguer gravity merged grid of Western Australia*, Geological Survey of Western Australia, Perth.

Brown BJ, Muller RD, Gaina C, Struckmeyer HIM, Stagg HMJ and Symonds PA (2003) 'Formation and evolution of Australian passive margins: implications for locating the boundary between continental and oceanic crust', in Hillis RR and Müller RD (eds) *Evolution and dynamics of the Australian Plate*, Geological Society of Australia Special Publication 22 and Geological Society of America Special Paper 372, pp 223–244.

Bunting JA and van de Graaff WJE (1977) 'Cundeelee, Western Australia: sheet SH 51–11 international index', *1:250,000 geological series – explanatory notes*', Geological Survey of Western Australia, Perth.

Catling DC and Zahnle KJ (2020) 'The Archean atmosphere', *Science Advances*, 6/9:1–16, doi:10.1126/sciadv.aax1420.

Cassidy KF, Champion DC, Krapež B, Barley ME, Brown SJA, Blewett RS, Groenewald PB and Tyler IM (2006) 'A revised geological framework for the Yilgarn Craton, Western Australia', *Record 2006/8*, Geological Survey of Western Australia, Perth.

Chin RJ, Hickman AH and Thom R (1984) 'Hyden, Western Australia: sheet SI 50–4 international index', *1:250,000 geological series – explanatory notes*, Geological Survey of Western Australia, Perth.

Chivas AR and Bird MI (1993) 'Palaeoclimate from Gondwanaland clays' in Churchman GJ, Fitzpatrick RW and Eggleton RA (eds) *Clays: Controlling the environment,* Proceedings of the 10th International clay conference, Adelaide, Australia.

Clark D (2004) 'Seismicity along the northern foreland of the Albany-Fraser Orogen' [unpublished report], Geoscience Australia (Earthquake Hazard Section).

Clark D (2010) 'Identification of Quaternary scarps in southwest and central west Western Australia using DEM-based hill shading: application to seismic hazard assessment and neotectonics', *International Journal of Remote Sensing*, 31/23:6297–6325.

Clark D, McPherson A and Collins C (2011) *Australia's seismogenic neotectonic record: A case for heterogeneous intraplate deformation,* Record 2011/11 Geoscience Australia.

Clarke JDA (1993) 'Stratigraphy of the Lefroy and Cowan palaeodrainages, Western Australia', *Journal of the Royal Society of Western Australia*, 76:13–23.

Clarke JDA (1994) 'Evolution of the Lefroy and Cowan palaeodrainage channels, Western Australia', *Australian Journal of Earth Sciences*, 41/1:55–68.

Clarke JDA, Bone Y and James NP (1996) 'Cool-water carbonates in an Eocene palaeoestuary, Norseman Formation, Western Australia', *Sedimentary Geology*, 101:213–226.

Clarke JDA, Gammon PR, Hou B and Gallagher SJ (2003) 'Middle to Upper Eocene stratigraphic nomenclature and deposition in the Eucla Basin', *Australian Journal of Earth Sciences*, 50:231–248.

Clitheroe G, Gudmundsson O and Kennett BLN (2000) 'The crustal thickness of Australia' *Journal of Geophysical Research*, 105-B6:13697–13713.

Cope RN (1975) 'Tertiary epeirogeny in the southern part of Western Australia', *Geological Survey of Western Australia, Annual Report 1974*, pp 40–46.

Czarnota K, Champion DC, Goscombe B, Blewett RS, Cassidy KF, Henson PA and Groenewald PB (2010) 'Geodynamics of the eastern Yilgarn Craton', *Precambrian Research*, 183:175–202, doi:10.1016/j.precamres.2010.08.004.

Czarnota K, Hoggard M, White N and Winterbourne J (2013) 'Spatial and temporal patterns of Cenozoic dynamic topography around Australia', *Geochemistry, Geophysics, Geosystems*, 14:634–658.

Dart RC, Barovich KM, Chittleborough DJ and Hill SM (2007) 'Calcium in regolith carbonates of central and southern Australia: Its source and implications for the global carbon cycle', *Palaeo*, 249(3):322–334.

De Broekert P and Sandiford M (2005) 'Buried inset-valleys in the eastern Yilgarn Craton, Western Australia: geomorphology, age and allogenic control', *Journal of Geology*, 113:471–493.

de Laeter JR and Lewis JD (1978) 'The age of the syenitic rocks of the Fitzgerald Peaks, near Norseman', *Annual report for the year 1977*, Geological Survey of Western Australia, Perth.

Dentith MC, Dent VF and Drummond BJ (2000) 'Deep crustal structure in the southwestern Yilgarn Craton, Western Australia', *Tectonophysics*, 325:227–255.

DiCaprio L, Gurnis M, Müller RD and Tan E (2009) 'Long-wavelength tilting of the Australian continent since the Late Cretaceous' *Earth and Planetary Science Letters*, 278:175–185, doi:10.1016/j.epsl.2008.11.030.

DiCaprio L, Gurnis M, Müller RD and Tan E (2011) 'Mantle dynamics of continentwide Cenozoic subsidence and tilting of Australia', *Lithosphere,* 3:311–316, doi:10.1130/L140.1.

Doepel JJG (1973) 'Norseman, Western Australia: sheet SI 51–2, international index', *1:250,000 geological series – explanatory notes*, Geological Survey of Western Australia, Perth.

Doublier MP (2013) 'Geological setting of mineral deposits in the Southern Cross district – a field guide', *Record 2013/11,* Geological Survey of Western Australia, Perth.

DPIRD (Department of Primary Industries and Regional Development) (2021) *Map Unit Database*, DPIRD, Western Australian Government, accessed July 2021.

Flament N, Coltice N and Rey PF (2008) 'A case for late-Archaean continental emergence from thermal evolution models and hypsometry', *Earth and Planetary Science Letters*, 275:326–336.

Flament N, Gurnis M and Müller RD (2013) 'A review of observations and models of dynamic topography', *Lithosphere,* 5:189–210, doi:10.1130/L245.1.

Gammon PR and James NP (2003) 'Paleoenvironmental controls on Upper Eocene biosiliceous neritic sediments, Southern Australia', *Journal of Sedimentary Research*, 73–6:957–972.

Gammon PR, James NP and Pisera A (2000) 'Eocene spiculites and spongolites in southwestern Australia: Not deep, not polar, but shallow and warm', *Geology,* 28:855–858, doi:10.1130/0091-7613(2000)28<855:ESASIS>2.0.CO;2.

Geoscience Australia National Earthquakes Alerts Centre, *Earthquake database,* earthquakes.ga.gov.au, accessed 22 July 2021.

Greff-Lefftz M, Robert B, Besse J, Frizon de Lamotte D and Vicente de Gouveia S (2017) 'Dynamic topography and lithospheric stresses since 400 Ma', *Geochemistry, Geophysics, Geosystems*, 18:2673–2700.

Griffin TJ (1989) 'Widgiemooltha, Western Australia: sheet SH 51–14 international index', 2nd edn, *1:250,000 geological series – explanatory notes*, Geological Survey of Western Australia, Perth.

Gurnis M, Moresi L and Müller D (2000) ‘Models of mantle convection incorporating plate tectonics: the Australia region since the Cretaceous’, in Richards MA, Gordon RG and van der Hilst RD (eds) *The History and Dynamics of Global Plate Motions*, American Geophysical Union, Washington, DC.

Gurnis M and Müller D (2003) ‘Origin of the Australian-Antarctic Discordance from an ancient slab and mantle wedge’, *Evolution and Dynamics of the Australian Plate,* Geological Society of Australia Special Publication 22 and Geological Society of America Special Paper 372, pp 417–430, doi:10.1130/0-8137-2372-8.417.

Hall CE and Jones SA (2008) ‘Geology of the Yardina 1:100,000 sheet’, *1:100,000 geological series explanatory notes*, Geological Survey of Western Australia, Perth.

Harrington L, Zahirovic S, Salles T, Braz C and Müller D (2019) ‘Tectonic, geodynamic and surface process driving forces of Australia’s paleogeography since the Jurassic’, in Keep M and Moss SJ (eds) *The Sedimentary Basins of Western Australia V: Proceedings of the Petroleum Exploration Society of Australia Symposium*, Perth.

Hazen RM, Papineau D, Bleeker W, Downs RT, Ferry JM, McCoy TJ, Sverjensky DA and Hexiong Y (2008) ‘Mineral evolution’, *American Mineralogist*, 93:1693–1720.

Hazen RM, Ewing, RC and Sverjensky DA (2009) ‘Evolution of uranium and thorium minerals’, *American Mineralogist*, 94:1293–1311.

Hazen RM (2010) ‘Evolution of minerals’, *Scientific American*, March 2010:58–65.

Heine C, Dietmar Müller R, Steinberger B and DiCaprio L (2010) ‘Integrating deep Earth dynamics in paleogeographic reconstructions of Australia’, *Tectonophysics*, 483:135–150.

Hill RI, Campbell IH and Compston W (1989) ‘Age and origin of granitic rocks in the Kalgoorlie-Norseman region of Western Australia: Implications for the origin of Archaean crust’, *Geochimica et Cosmochimica Acto*, 53:1259–1275.

Hocking RM (1990a) ‘Eucla Basin’, *The geology and mineral resources of Western Australia Memoir 3,* Geological Survey of Western Australia, pp 548–560.

Hocking RM (1990b) ‘Bremer Basin’, *The geology and mineral resources of Western Australia Memoir 3*, Geological Survey of Western Australia, pp 561–564.

Hoggard MJ, Austermann J, Randel C and Stephenson S (2021) ‘Observational estimates of dynamic topography through space and time’, in Marquardt H, Ballmer M, Cottaar S and Konter J (eds) *Mantle convection and surface expressions*, AGU Geophysical Monograph Series, Washington, DC.

Honing D, Hansen-Goos H, Airo A and Spohn T (2014) ‘Biotic vs. abiotic Earth: A model for mantle hydration and continental coverage’, *Planetary and Space Science*, 98:5–13.

Hou B, Frakes LA, Sandiford M, Worrall L, Keeling J and Alley NF (2008) ‘Cenozoic Eucla Basin and associated palaeovalleys, southern Australia — Climatic and tectonic influences on landscape evolution, sedimentation and heavy mineral accumulation’, *Sedimentary Geology*, 203:112–130.

Hystad G, Morrison SM and Hazen RM (2019) ‘Statistical analysis of mineral evolution and mineral ecology: The current state and a vision for the future’, *Applied Computing and Geosciences*, 1:1–5.

James NP, Boreen TD, Bone Y and Feary DA (1994) ‘Holocene carbonate sedimentation on the west Eucla Shelf, Great Australian Bight: a shaved shelf’, *Sedimentary Geology*, 90:161–177.

Jennings JN and Mabbutt JA (1977) 'Physiographic outlines and regions' in Jeans DN (ed) *Australia – A geography,* Sydney University Press.

Johnson TE, Brown M, Gardiner NJ, Kirkland CL and Smithies RH (2017) 'Earth's first stable continents did not form by subduction', *Nature*, 543:239–242.

Jones BG (1990) 'Cretaceous and Tertiary sedimentation on the western margin of the Eucla Basin', *Australian Journal of Earth Sciences*, 37:317–329.

Kirkland CL, Wingate MTD, Spaggiari CV and Pawley MJ (2010) '194731: psammitic gneiss, Ponton Creek', *Geochronology Record 860*, Geological Survey of Western Australia, Perth.

Konhauser KO, Planavsky NJ, Hardisty DS, Robbins LJ, Warchola TJ, Haugaard R, Lalonde SV, Partin CA, Oonk PBH, Tsikos H, Lyons TW, Bekker A and Johnson CM (2017) 'Iron formations: A global record of Neoarchaean to Palaeoproterozoic environmental history', *Earth-Science Reviews*, 172:140–177.

Krapez B, Barley ME and Brown SJA (2008a) 'Late Archaean synorogenic basins of the Eastern Goldfields Superterrane, Yilgarn Craton, Western Australia Part I, Kalgoorlie and Gindalbie Terranes', *Precambrian Research*, 161:135–153.

Krapez B, Standing JG, Brown SJA and Barley ME (2008b) 'Late Archaean synorogenic basins of the Eastern Goldfields Superterrane, Yilgarn Craton, Western Australia Part II, Kurnalpi Terrane,' *Precambrian Research*, 161:154–182.

Krapez B and Barley ME (2008) 'Late Archaean synorogenic basins of the Eastern Goldfields Superterrane, Yilgarn Craton, Western Australia Part III, Signatures of tectonic escape in an arc-continent collision zone', *Precambrian Research*, 161:183–199.

Libby J, Graves DI and Vearncombe JR (1990) 'The nature and tectonic significance of the crustal-scale Koolyanobbing shear zone, Yilgarn Craton, Western Australia', *Australian Journal of Earth Sciences*, 38/2:229–245.

Lowry DC (1970) 'Geology of the Western Australian part of the Eucla Basin', *Bulletin 122,* Geological Survey of Western Australia, Perth.

Martin DMcB, Hocking RM, Riganti A and Tyler IM (2020) *1:2 500 000 geological map of Western Australia, November 2020 update*, Geological Survey of Western Australia, Perth.

Mindat (2021) *Colville Sandstone* [map], mindat.org/paleo_strat.php?id=3913, accessed June 2021.

Mole DR, Fiorentini ML, Cassidy KF, Kirkland CL, Thebaud N, McCuaig TC, Doublier MP, Duuring P, Romano SS, Maas R, Belausova EA, Barnes SJ and Miller J (2013) 'Crustal evolution, intra-cratonic architecture and the metallogeny of an Archaean craton', in Jenkin GRT, Lusty PAJ, Mcdonald I, Smith MP, Boyce AJ and Wilkinson JJ (eds) *Ore Deposits in an Evolving Earth*, Special Publications 393, Geological Society, London, doi:org/10.1144/SP393.8.

Mole DR, Kirkland CL, Fiorentini ML, Barnes SJ, Cassidy KF, Isaac C, Belausova EA, Hartnady M and Thebaud N (2019) 'Time-space evolution of an Archean craton: A Hf-isotope window into continent formation', *Earth-Science Reviews,* 196:102831

Mory AJ, Redfern J and Martin JR (2008) 'A review of Permian–Carboniferous glacial deposits in Western Australia' in Fielding CR, Frank TD and Isbell JL (eds) *Resolving the Late Paleozoic ice age in time and space*, Special Paper 441, Geological Society of America.

Müller RD, Hassan R, Gurnis M, Flament N and Williams SE (2018) ‘Dynamic topography of passive continental margins and their hinterlands since the Cretaceous,’ *Gondwana Research*, 53:225–251, doi:10.1016/j.gr.2017.04.028.

Myers JS (1995) ‘Geology of the Esperance 1:100,000 sheet’, *1:100,000 geological series explanatory notes*, Geological Survey of Western Australia, Perth.

Neumayr P, Walshe J, Connors K, Cox S, Morrison RS, Stolz E and Harris M (2004) ‘Gold mineralization in the St Ives camp near Kambalda’, in Neumayr P, Harris M and Beresford SW (eds) *Gold and nickel deposits in the Archaean Norseman-Wiluna greenstone belt, Yilgarn Craton, WA – A field guide*, vol 2004/16, pp 23–45, Geological Survey of Western Australia, Perth.

Pain C, Gregory L, Wilson P and McKenzie N (2011) *The physiographic regions of Australia, Explanatory notes*, Australian Collaborative Land Evaluation Program and National Committee on Soil and Terrain.

Parnell J and Brolly C (2021) ‘Increased biomass and carbon burial 2 billion years ago triggered mountain building’, *Communications Earth & Environment*, 2:238:1–9.

Pawley MJ, Wingate MTD, Kirkland CL, Wyche S, Hall CE, Romano SS and Doublier MP (2012) ‘Adding pieces to the puzzle: Episodic crustal growth and a new terrane in the northeast Yilgarn Craton, Western Australia’, *Australian Journal of Earth Sciences,* 59:603–623.

Perring CS, Barnes SJ and Hill RET (1995) ‘The physical volcanology of Archean komatiite sequences from Forrestania, Southern Cross Province, Western Australia’, *Lithos*, 34:189–207.

Perring CS, Barnes SJ and Hill RET (1996) ‘Geochemistry of komatiites from Forrestania, Southern Cross Province, Western Australia: evidence for crustal contamination’, *Lithos*, 37:181–197.

Quentin de Gromard R, Spaggiari CV, Munro M, Sapkota J and De Paoli M (2017) ‘SGTSG 2017 Albany-Fraser Orogen pre-conference field trip: Transect across an Archean craton margin to a Proterozoic ophiolite’, *Record 2017/14*, Geological Survey of Western Australia, Perth.

Reading AM, Kennett BLN and Dentith MC (2003) ‘Seismic structure of the Yilgarn Craton, Western Australia’, *Australian Journal of Earth Sciences*, 50:427–438.

Rey P and Houseman G (2006) ‘Lithospheric scale gravitational flow: the impact of body forces on orogenic processes from Archaean to Phanerozoic’, *Geological Society London Special Publications*.

Romano SS, Thebaud N, Mole DR, Wingate MTD, Kirkland CL and Doublier MP (2014) ‘Geochronological constraints on nickel metallogeny in the Lake Johnston belt, Southern Cross Domain’, *Australian Journal of Earth Sciences*, 61/1:143–157.

Salama R (1994) ‘The evolution of saline lakes in the relict drainage of the Yilgarn River, Western Australia’, in Renaut RW and Last WM (eds) *Sedimentology and Geochemistry of Modern and Ancient Saline Lakes*, Society for Sedimentary Geology, SEPM Special Publication No 50, doi:10.2110/pec.94.50.0189.

Sandiford M (2007) ‘The tilting continent: A new constraint on the dynamic topographic field from Australia’, *Earth and Planetary Science Letters*, 261:152–163.

Sandiford M, Quigley M, De Broekert P and Jakica S (2009) ‘Tectonic framework for the Cenozoic cratonic basins of Australia’, *Australian Journal of Earth Sciences*, 56:S5–S18.

Schofield A and Totterdell J (2008) *Distribution, timing and origin of magmatism in the Bight and Eucla Basins*, Geoscience Australia Record 2008/24, Geoscience Australia.

Sircombe KN and Freeman MJ (1999) 'Provenance of detrital zircons on the Western Australia coastline—Implications for the geologic history of the Perth basin and denudation of the Yilgarn Craton', *Geology*, 27:879–882.

Sippl C, Brisbout L, Spaggiari CV, Gessner K, Tkalcic H, Kennett BLN and Murdie R (2017) 'Crustal structure of a Proterozoic craton boundary: East Albany-Fraser Orogen, Western Australia, imaged with passive seismic and gravity anomaly data', *Precambrian Research*, 296:78–92.

Smithies RH, Lu Y, Johnson TE, Kirkland CL Cassidy KF, Champion DC, Mole DR, Zibra I, Gessner K, Sapkota J, De Paoli MC and Poujol M (2019) 'No evidence for high-pressure melting of Earth's crust in the Archean', *Nature Communications*, 10:55–59, doi:10.1038/s41467-019-13547-x.

Spaggiari CV, Bodorkos S, Barquero-Molina M, Tyler IM and Wingate MTD (2009) 'Interpreted bedrock geology of the South Yilgarn and central Albany-Fraser Orogen, Western Australia', *Record 2009/10*, Geological Survey of Western Australia, Perth.

Spaggiari CV, Kirkland CL, Pawley MJ, Smithies RH, Wingate MTD, Doyle MG, Blenkinsop TG, Clark C, Oorschot CW, Fox LJ and Savage J (2011) 'The geology of the east Albany-Fraser Orogen – a field guide', *Record 2011/23*, Geological Survey of Western Australia, Perth.

Spaggiari CV, Kirkland CL, Smithies RH, Occhipinti SA and Wingate MTD (2014a) 'Geological framework of the Albany-Fraser Orogen', in Spaggiari CV and Tyler IM (eds) *Albany-Fraser Orogen seismic and magnetotelluric (MT) workshop 2014: extended abstracts*, Record 2014/6, Geological Survey of Western Australia, Perth.

Spaggiari CV, Kirkland CL, Smithies RH and Wingate MTD (2014b) 'Tectonic links between Proterozoic sedimentary cycles, basin formation and magmatism in the Albany-Fraser Orogen', *Report 133*, Geological Survey of Western Australia, Perth.

Squire R, Cas R, Clout J and Behets R (1998) 'Volcanology of the Archaean Lunnon Basalt and its relevance to nickel sulfide-bearing trough structures at Kambalda, Western Australia', *Australian Journal of Earth Sciences,* 45:695–715, doi:10.1080/08120099808728427.

Stark JC, Wang X, Denyszyn SW, Li Z, Rasmussen B, Zi J, Sheppard S and Liu Y (2019) 'Newly identified 1.89 Ga mafic dyke swarm in the Archean Yilgarn Craton, Western Australia suggests a connection with India', *Precambrian Research*, 329:156–169.

Swager CP, Goleby BR, Drummond BJ, Rattenbury MS and Williams PR (1997) 'Crustal structure of granite-greenstone terranes in the Eastern Goldfields, Yilgarn Craton, as revealed by seismic reflection profiling', *Precambrian Research*, 83:43–56.

Tille P (2006) 'Soil-landscapes of Western Australia's rangelands and arid interior', *Resource management technical report 313*, Department of Agriculture and Food, Western Australian Government.

Torsvik TH, van der Voo R, Doubrovine PV, Burke K, Steinberger B, Ashwal LD, Trønnes RG, Webb SJ and Bull AL (2014) 'Deep mantle structure as a reference frame for movements in and on the Earth', *Proceedings of the National Academy of Science USA,* 111:8735–8740, doi:10.1073/pnas.1318135111.

Verboom WH and Galloway PD (2000) 'Hypothetical effects of rhizosphere associates of Proteaceae and their lateritic products on landscape evolution: explanatory descriptions from southwestern Australia', in Tang C and Williamson DR (eds) *Proceedings of the Australian*

Society of Soil Science Inc. (WA Branch) and Environmental Consultants Association (WA) Inc. Soils 2000 conference, Muresk Institute of Agriculture, Western Australia.

Von der Borch CC (1967) 'Southern Australian submarine canyons: their distribution and ages', *Marine Geology*, 6:267–279.

Waddell PA, Timms NE, Spaggiari CV, Kirkland CL and Wingate MTD (2015) 'Analysis of the Ragged Basin, Western Australia: insights into syn-orogenic basin evolution within the Albany-Fraser Orogen', *Precambrian Research*, 261:166–187.

Wang X, Zhu P, Kusky TM, Zhao N, Li X and Wang Z (2016) 'Dynamic cause of marginal lithospheric thinning and implications for craton destruction: a comparison of the North China, Superior, and Yilgarn cratons', *Canadian Journal of Earth Sciences*, 53:1121–1141.

Wasson RJ and Hyde R (1983) 'Factors determining desert dune type', *Nature*, 304:337–339.

Weinberg RF and van der Borgh P (2008) 'Extension and gold mineralization in the Archean Kalgoorlie Terrane, Yilgarn Craton', *Precambrian Research*, 161:77–88.

Wilde SA, Valley JW, Peck WH and Graham CM (2001) 'Evidence from detrital zircons for the existence of continental crust and oceans on Earth 4.4Gyr ago', *Nature*, 409:175–178 doi:10.1038/35051550.

Wingate MTD (2017) 'Mafic dyke swarms and large igneous provinces in Western Australia get a digital makeover', *GSWA 2017 extended abstracts: Record* 2017/2, Geological Survey of Western Australia, Perth.

Witt WK, Cassidy K, Lu Y and Hagemann S (2020) 'The tectonic setting and evolution of the 2.7 Ga Kalgoorlie - Kurnalpi Rift, a world-class Archean gold province', *Mineralium Deposita*, 55:601–631, doi:10.1007/s00126-017-0778-9.

Wyche S (2014) 'Geological setting of mineral deposits in the eastern Yilgarn Craton – a field guide', *Record 2014/10,* Geological Survey of Western Australia, Perth.

Wyche S, Fiorentini ML, Miller JL and McCuaig TC (2012) 'Geology and controls on mineralisation in the Eastern Goldfields region, Yilgarn Craton, Western Australia', *Episodes, Journal of International Geoscience*, 35:273–282, doi:10.18814/epiiugs/2012/v35i1/027.

Wyche S, Nelson DR and Riganti A (2004) '4350–3130 Ma detrital zircons in the Southern Cross Granite–Greenstone Terrane, Western Australia: implications for the early evolution of the Yilgarn Craton', *Australian Journal of Earth Sciences,* 51:31–45, doi:10.1046/j.1400-0952.2003.01042.x.

Zecchin M, Catuneanu O and Caffau M (2019) 'Wave-ravinement surfaces: Classification and key characteristics', *Earth-Science Reviews*, 188:210–239.

Zhu Z, Campbell IH, Allen CM, Brocks JJ and Chen B (2022) 'The temporal distribution of Earth's supermountains and their potential link to the rise of atmospheric oxygen and biological evolution', *Earth and Planetary Science Letters,* 580:117391, doi:10.1016/j.epsl.2022.117391.

5 Soils

PD Galloway

Introduction

In this chapter, we describe the soil classification systems used during this survey and explain how the survey was instrumental in modifying WA's general-purpose classification to account for soils of the rangelands. We present a synopsis of soil distribution and variation across the survey area, a section about soil formation that summarises biogeochemical processes contributing to soil development and evolution, and a section on soil surface features that retard erosion.

We grouped soils with morphological similarities into suites that reveal spatial and genetic links, and we describe each common soil, or soil suite, in terms of their distribution across the survey area and within land systems (see Land systems Volume 2, Chapter 7). The key qualities of soil and land surfaces relevant to land degradation processes in relation to land management practices are also outlined.

Soil classification

Soil classification systems are a means of communicating information about properties that are relevant to land use and soil management. Soil and land surveys in WA use the Western Australian Soil Group (WA Soil Group) classification to identify the main soil types and communicate their characteristics to a general audience (Schoknecht and Pathan 2013). This classification describes and names soils using recognisable morphological features relevant to WA. The soil groups are combined with landform descriptions in the DPIRD soil-landscape mapping system to form the basis of the DPIRD land evaluation framework. Using WA Soil Groups to classify soils within the survey area is an essential precursor for future assessments of land capability.

However, the Schoknecht and Pathan (2013) version of WA Soil Groups focuses on soil types common to the dryland agriculture areas of south-west WA. It does not explicitly classify all WA soils. This survey exposed these limitations, especially for soils dominated by calcareous materials and for skeletal (shallow and rocky) soils. Consequently, this survey triggered a revision of WA Soil Groups to cater for all WA soils.

In this survey, we also used the Australian Soil Classification (ASC), which is the national system for classifying soils. It uses scientific, soil-based nomenclature like other classification systems of the world. We used the second edition of the ASC (Isbell 2016). This edition was recently updated (Isbell and NCST 2021) to reflect the widespread presence of deep sandy soils prominent across the survey area and more generally throughout WA and arid inland Australia. This revision by the National Committee on Soil and Terrain has modified the classification of sandy soils, which now classify as Arenosols in alignment with other world classifications (e.g. IUSS Working Group WRB 2015). However, we used Isbell (2016) and classified sandy soils as Tenosols because the revisions occurred too late to revise our soil observation classifications.

Throughout this bulletin, the southern Goldfields soils are categorised by the revised WA Soil Group classification (Galloway et al. in press) and the typical ASC (Isbell 2016). Of the 663 inventory sites used in this survey (see Methods chapter), 635 sites had sufficient data to classify to the revised WA Soil Groups. At the start of the survey, 28 sites were assigned a 2013 WA Soil Group classification (Schoknecht and Pathan 2013) during field investigations conducted without a soil surveyor.

Synopsis of soil distribution

The complex and varied soil distribution of the survey area is due to complex geology, geomorphological history and the significant climate gradient. This results in a diversity of ecological habitats that further modify soil features over time.

The survey area straddles the south-eastern-most part of the Archean Yilgarn Craton and is bisected by Ida Fault, a major north-trending lineament that differentiates the west, which contains granites and gneisses, from the east, which contains volcano-sedimentary greenstones and small granite intrusions. Bedrock at the south of the survey area is the complex Proterozoic Albany-Fraser Orogen, which is sutured to the Yilgarn Craton's south-eastern margin. The Proterozoic bedrock of the south-east retains a veneer of sandy and calcareous shallow marine sediments of the Cenozoic Eucla and Bremer basins. A small part of the north-east has Mesozoic sandy sediments deposited in the Officer and Canning basins.

Relative relief and regional valley gradients are low. Broad, subdued uplands demarcate major catchments. Locally resistant bedrock and actively eroding subcatchment headwaters occasionally form prominent steep hills above the subdued surrounds. Short rivers flow from the southern margins to the south coast. North of the south coast divide, the internally drained Lake Tay catchment was prehistorically connected to Lake Dundas and the south coast drainage network. This is now entirely occluded, so erosive stripping and sediment redistribution is local and dominated by eolian processes. To the north of Lake Tay catchment lies the Lake Johnston system, which flows east to Lake Lefroy and then the Nullarbor region. North of the Lake Johnston catchment lie headwaters that flow north to Lake Deborah and then west through the Swan–Avon drainage. Lake Deborah catchment is uppermost of the Swan–Avon drainage and is most remote from regional incision and stripping, so retains extensive deep regolith. The north-eastern and central part of the survey area drains east to the Nullarbor plain via several salt lake chains and Ponton Creek. This area has a steeper regional gradient than the west, contains more erosive soils and is more affected by regional stripping. This drainage is bounded to the west by Ida Fault, which limits headward incision. The mixed granite and greenstone geology here influences geomorphology and results in complex patterns of weathering, erosion and deposition.

Soils of the sandy Canning and Officer basins sediments are characterised by sandplains and dunefields dominated by Yellow deep sand (Yellow-Orthic Tenosol) vegetated with spinifex grassland.[1] Wind has shaped the sand into linear dunes and swales with a generally east-north-east orientation.

In the north, Yellow and Red deep sands (Yellow-Orthic and Red-Orthic Tenosols) also occupy sandplains that form from granite and gneiss on broad catchment divides. In the far north, these landforms are vegetated by spinifex grassland and open eucalypt woodland growing on Red deep sand. Further south, the granitic sandplain has experienced a different climate and ecological history, resulting in sandplain of Yellow deep sand vegetated by Kwongan heath. Granitic and gneissic bedrock extends further south, and soils change from sandplain to various grey sandy duplex soils with alkaline subsoils (Brown and Grey Sodosols), vegetated mostly by low eucalypt (mallee) woodland and scrub. Broad uplands across the south-west, which surround the south coast and Tay catchments, have soils with ironstone gravels in a grey sandy matrix, usually with a clay subsoil (Petro-ferric Grey and Yellow Sodosols). Further north, interfluves surrounding headwaters of Johnston and Deborah catchments have ironstone gravelly soils (Sesqui-nodular Tenosols) on crests and on breakaways that form at the erosion

[1] For soil names, the first classification is WA Soil Group and the related ASC is listed in brackets, for example, Yellow deep sand (Yellow-Orthic Tenosol).

front bordering yellow sandplain zones. Ironstone gravelly soils also form breakaways and mesas on geological faults and shear zones, notably the prominent scarps along Ida Fault.

Granite diapirs and tors are resistant to erosion and protrude above plains and rises. Granite domes are generally devoid of soil and vegetation and are classed as Bare rock. Where soils have developed around outcrops, they are stony soils (Lithic Leptic Rudosols), shallow sand soils and shallow loam soils (Gritty Arenic Rudosols). These soils are red in the north and yellow or brown in the south.

The central and northern part of the survey area east of Ida Fault consists of extensive greenstone belts intruded by granite diapirs. Minerals in greenstone are richer in iron and magnesium than those in granite, and they weather more easily to form iron-rich and clay-rich soils. Granite is more resistant. This landscape has been extensively stripped by sequential 'waves' of erosion. Some subcatchments contain knickpoints (gradient changes) with granite at their base, which slows watershed and reduces erosion These subcatchments retain more sediment, are more deeply weathered and have subdued relief in upper parts. Conversely, subcatchments lacking effective armouring at their knickpoints are more eroded, have more exposed rock and have steeper gradients in upper parts. Over geological time as the regional erosion front progresses west, the lower eastern catchments continue to weather. Consequently, eastern landforms are generally more deeply weathered, have thicker regolith and less fresh rock.

A consequence of variable erosion is that young subcatchments and those lacking knickpoints have unweathered rocky headwaters mantled by stony soils. These generate fresh run-off and form valleys with fresh and brackish ephemeral rivers, and terminal swamps and lakes with Cracking clay soils (Vertosols) and only minor salt accumulation. Conversely, old subcatchments have deeply weathered headwaters with ironstone gravel interfluves and plains containing deep loamy soils that are often calcareous (Calcarosols, Red Kandosols, Red and Brown Dermosols). These store salt and generate brackish run-off, forming salt lake chains with saline soils (various Hydrosols). Trunk valleys lie at the termini of both types of subcatchment. They have large salt lakes with salt lake soils (Hypersalic Hydrosols) and saline soils.

Interfluves of the lower regional catchment are more subdued and deeply weathered than interfluves in the regional catchment headwaters. Thus, lower catchment interfluves have rounded rises – breakaways are subdued or absent – and soils are Loamy ironstone gravels (Ferric Red and Ferric Brown Kandosols) and calcareous loams (Calcarosols). In contrast, regional catchment headwaters (near Ida Fault and west of Ora Banda) have prominent breakaways with shallow ironstone gravelly soils (Sesqui-nodular Tenosols).

Hillcrests of the eastern granite and greenstone are dominated by stony soils (Rudosols) on the various rock substrates. Soils formed on granite are as previously described. Soils formed on basalt are stony soils and shallow loam soils (Lithic Rudosols). These commonly have carbonate accumulations and are Calcareous stony soil and Calcareous shallow loam (Lithic Calcic Calcarosols). Soils formed on ultramafic and volcanoclastic sediments have accumulations of calcium from primary minerals and marine sources. These form various loamy calcareous soils (Lithic and Paralithic Calcarosols). Siliceous volcanoclastic sediments often have salt accumulations.

Run-off from crestal stony soils carries sediment via sheet flow over broad, gently undulating plains. Soils of these plains are distinctive north and south of the South-western Interzone (see Vegetation and habitat type ecology chapter) because vegetation transitions from mulga-dominated (*Acacia aneura* and relatives) in the north to eucalypt-dominated in the south, coinciding with a significant climate gradient. The soil differences are caused by the vegetation and their microbial root associates. The northern sheet flow plains are vegetated by mulga and have red earth with hardpan and Red–brown hardpan shallow loam (Duric Red Dermosols, Duric Red Chromosols). In contrast, the southern sheet flow plains are vegetated by eucalyptus and have alkaline red loamy duplex soils (Red and Brown Sodosols), Red loamy earth (Red Dermosols) and various calcareous loamy earth soils (Calcarosols).

The sheet flow coalesces in broad valley floors characterised by Red loamy earth (Red Dermosols) and alkaline red loamy duplex soils (Red Chromosols) and red and brown clay soils with calcareous subsoils (Calcic, Red and Brown Dermosols) vegetated by eucalypt woodland with chenopod understorey. The lowest landscape positions have salt lake chains with Saline wet soil and Salt lake soil (Hydrosols) vegetated by halophytes, or bare.

Two major marine transgressions have affected the south-east and central southern parts of the survey area over the Cenozoic era. These events eroded prior landforms, planed them to low relief, and deposited distinctive sedimentary parent materials that now influence soil variation. In the east, carbonate sediments dominate, resulting in calcareous soils that have been biologically altered to form calcareous concretions and hardpans within the soil profile. The soil fine fraction (<2 mm) is calcareous and has predominantly light (sandy) to moderate (sandy loam to sandy clay loam) texture. These landforms mostly contain Calcareous sandy earth and Calcareous gravelly sandy earth (Calcarosols) vegetated mostly by *Eucalyptus oleosa* subsp. *oleosa* (giant mallee) and *Melaleuca* spp. (boree) woodland over *Cratystylis conocephala* (false bluebush) dominated understorey. In the central southern area, the sediments have a high proportion of fine sandy and silty sediments and retain a calcareous signature. Soils that form from this parent material generally have sandy or loamy surface textures, underlain by calcareous clay subsoil. They are classed as Calcareous sandy earth, Calcareous loamy earth and Calcareous gravelly loamy earth (Supracalcic and Hypercalcic Calcarosols) and are vegetated by mallee scrub and melaleuca heath. Throughout this marine transgression-affected area, subdued low rises of crystalline bedrock, which have skeletal rocky and stony soils (Rudosols), occasionally protrude through the depositional surface.

Crystalline basement rocks that remained as islands during transgressive phases form more prominent ridges and hills in the south-east. The most prominent examples are the iron-rich mafic and ultramafic Proterozoic rocks that form the Jimberlana Dyke suite, Fraser Range and Southern Hills. These rocky protrusions emerge from the sandy calcareous marine plain and have shallow rocky soils (Leptic Rudosols) on their crests. Their upper slopes have Red shallow loam (Lutic and Clastic Rudosols) and mid to lower slopes have Red loamy earth (Calcic Red Dermosols) and Calcareous loamy earth (Hypercalcic and Calcic Calcarosols). Red clay soils (Red Dermosols) and cracking clay soils (Self-mulching Vertosols, Epipedal Vertosols) occupy lower slopes and drainage foci, respectively.

The region experiences low rainfall and evaporation in excess of rainfall for much of each year. Salts have accumulated to a great degree in the regolith and soil, causing formation of extensive and large salt lake chains across most valley floors. Lake beds are hypersaline (Hypersalic Hydrosols) and devoid of vegetation, but periodic flooding occurs, winnowing the surficial sediments and contributing to source materials that blow out after the lakes dry up. The wind-eroded materials deposit mostly to the south-east of the lake systems, forming extensive calcareous sand dunes and sandsheets of Yellow deep sand (Arenic Yellow-Orthic Tenosols), Calcareous deep sand (Calcarosols) and Calcareous gravelly deep sand (Hypercalcic Calcarosols). Local hydrological characteristics sometimes cause gypsum dunes (Hypergypsic Calcarosols) and clayey calcareous parna (Hypercalcic Calcarosols) to deposit proximal to the south-eastern shores of lakes as small crescent-shaped dunes. These deposits are most common at lake margins in the south and east of the survey area, probably due to the influence of marine deposition and the higher concentration of sulfur minerals in the groundwater. However, they are common features of many salt lakes.

Soils in the survey area

Our investigations at inventory sites identified the presence of 69 of the 111 WA Soil Groups. This great diversity reflects the complexity and diversity of the landscapes and vegetation associations present. These soils occupy all 12 soil supergroups (Table 5.1), which are suites of soil groups with similar important morphological characteristics. We are confident an additional 6 soil groups are present even though they were not encountered during field investigations because of limitations described in the Methods chapter. The soil groups present and the number of times each soil was encountered at inventory sites, are presented in Volume 2, Appendix C, grouped by soil supergroups.

We place the 69 WA Soil Groups present in the survey area into context by grouping individual but related soils that often occur together in the landscape into broader soil supergroups, ordered according to the keys in Galloway et al. (in press) (Table 5.2 to Table 5.12). Each soil group is summarily described along with the landforms and land systems they are commonly found on, as determined by our observations and inferred presence from similar land systems in surrounding surveys. Information in italics indicates that the soil is likely to be present but was not classified or identified during site investigations.

A suite of soil-like materials classifies at the supergroup level in the WA Soil Groups as ‘undifferentiated soils’. We identified 2 sites in drainage tracts where the soil was recently deposited layered alluvium, which we classified as Undifferentiated soils. We also mapped landforms highly disturbed by human activity, including mine sites and townships, and these were classified as Undifferentiated soils, although we did not describe any such sites. Finally, sites described for vegetation characteristics but not soils were assigned as Undifferentiated soils. None of these soil-like materials are described further.

Table 5.1: Soil supergroups in WA

Soil supergroup	Reference table
Saline and wet soils	Table 5.2
Ironstone gravelly soils	Table 5.3
Shallow, rocky or stony soils	Table 5.4
Shallow sand soils	Table 5.5
Sandy duplex soils	Table 5.6
Sandy earth soils	Table 5.7
Deep sand soils	Table 5.8
Clay soils	Table 5.9
Shallow loam soils	Table 5.10
Loamy duplex soils	Table 5.11
Loamy earth soils	Table 5.12

Note: Supergroups are ordered by the classification keys in Galloway et al. (in press).

Table 5.2: Summary of soil supergroup Saline and wet soils

WA Soil Group	Description	Common landforms	Common land systems
Saline soil	Soil is moderately to highly saline (>800 EC_e mS/m) and is not seasonally wet within 80 cm; variably textured saline soils	Saline alluvial plains, lake margins and saline stony plains, but can be where salts accumulate, especially on saline basement rock or in drainage depressions	Carnegie, Dunnsville, Lefroy, Monger, Moorebar, Ponton, Woorbla, Yardina; minor group in Cundlegum, Kanowna, Lawrence
Saline wet soil (Likely to be present)	*Soil is at least moderately saline (>400 EC_e mS/m) within 80 cm and wet; variably textured saline soils*	*Saline plains, lake margins of salt lake chains, playa lakes, major drainage tracts and drainage depressions*	*Burdett, Carnegie, Cheriton, Cronin, Hope, Lagan, Lake Deborah, Lefroy, Ponton, Sharpe, Woorbla, Yardina; minor group in Dunnsville*
Salt lake soil	Soil is highly saline and wet because of primary salinity; hypersaline with abundant gypsum crystals at depth, usually in a clayey matrix	Salt lakes and playas; dominant on lake beds	Burdett, Carnegie, Cheriton, Cronin, Halbert, Hope, Lagan, Lake Deborah, Lefroy, Yardina Minor in Hope, Hopeside, Sharpe
Wet soil and *Semi-wet soil* (Likely to be present)	*Soil is wet for extended periods; commonly with loamy or clayey matrix)*	*Fresh lakes, playas, swamps*	*Buraminya, Cronin, Emu, Rowles Minor in Forrestania, Hope, Noondoonia, Salmon Gums*

A salt lake in the Yardina land system showing a salt lake soil in the foreground

Table 5.3: Summary of soil supergroup Ironstone gravelly soils*

WA Soil Group	Description	Common landforms	Common land systems
Calcareous loamy ironstone gravel (Like Shallow calcrete ironstone gravel but deeper)	Ironstone gravelly soil with a predominantly loamy matrix that is mostly calcareous	Breakaways, calcrete pavements, colluvial slopes, footslopes, hillslopes, loamy plains with ironstone lag, low rises, ridges and hillcrests, stony plains	Hampton, Helag, Illaara, Jackson, Johnston, Latimore, Moriarty, Tealtoo; minor group in Bungalbin
Deep sandy gravel	Ironstone gravelly soil with a predominantly sandy matrix that extends beyond 80 cm	Gravelly sandsheets, sandplain and sandsheets	Bannar, Hyden, Ironcap, Joseph, Newdegate
Loamy gravel	Ironstone gravelly soil with a predominantly loamy matrix, often grading to clay by 80 cm	Footslopes, hillslopes, low rises, loamy plains, loamy plains with ironstone lag	Helena, Illaara, Jackson, Latimore; minor group in Bannar, Bungalbin
Sandy surfaced earthy gravel	Ironstone gravelly soil with a sandy surface texture that grades to loam or clay by 80 cm	Gravelly sandsheets	Minor group in Bannar, Hyden, Illaara, Joseph
Shallow calcrete ironstone gravel (Like Calcareous loamy ironstone gravel but shallower)	Ironstone gravelly soil with a cemented calcrete hardpan evident within 30–80 cm; usually has a loamy soil matrix overprinted by calcium carbonate	Breakaways, calcrete pavements, hillcrests, hillslopes, loamy plains with ironstone lag, low rises, ridges	Dunnsville, Hampton, Helag, Illaara, Jackson, Jaurdi, Latimore, Marda, Monger, Moriarty, Tealtoo; minor group in Bungalbin
Shallow duplex sandy gravel (Rare soil)	Ironstone gravelly soil with a sandy matrix and a texture contrast layer within 30 cm	Gravelly sandsheets, low rises, undulating plains	Newdegate
Shallow loamy gravel (Like Very shallow soil over ferricrete hardpan [Table 5.4] but deeper)	Ironstone gravelly soil with a loamy matrix over ferricrete hardpan evident within 30–80 cm; most commonly forms on mafic and ultramafic basement rock	Breakaways, hillcrests, hillslopes, footslopes, loamy plains with ironstone lag, low rises, ridges; occasionally on breakaway footslopes	Bevon, Bungalbin, Greenmount, Helena, Hyden, Illaara, Jackson, Latimore, Monger, Newdegate; minor group in Bannar
Shallow sandy gravel (Like Very shallow soil over ferricrete hardpan [Table 5.4] but deeper)	Ironstone gravelly soil with a sandy matrix over ferricrete hardpan or rock evident within 30–80 cm	Breakaways, gravelly sandsheets, loamy plains, low rises, sandplains, sandsheets	Bannar, Euchre, Hyden, Ironcap, Joseph, Newdegate

* Ironstone gravelly soil is defined as any soil that continues beyond 30 cm deep and that has a soil layer that starts within 15 cm of the surface, is at least 20 cm deep and contains greater than 20% ironstone gravels by visual estimation.

Table 5.4: Summary of soil supergroup Shallow, rocky or stony soils

WA Soil Group	Description	Common landforms	Common land systems
Bare rock	Rock outcrop (excludes outcrops of hardpan or cemented layers); lacks soil material or has only a sparse, thin (<6 cm) veneer of weathered rock minerals; all rock types (fractured rock containing soil material in fissures that support vegetation is included)	Domes, hillcrests, hills, hillslopes, low rises, pediments*, ridges, tors	Balladonia, Bandy, Bungalbin, Dryandra, Gnamma, Greenmount, Kartukartunga, Kurrawang, Kwelkan, Noganyer, Norie, Quartzitehill, Sedgeman, Wallaroo, Wyralinu; minor group in Bevon, Charlina, Graves, Hann, Jaurdi, Kanowna, Lawrence, Symons
Calcareous stony soil (Like Calcareous very shallow soil but deeper)	Soil is deeper than 30 cm and contains many gravels and stones; most of the soil is calcareous; soil texture is usually loam or clay; most commonly occurs on mafic and volcaniclastic basement rock, except in Eundynie land system where it is formed on spongolite (Figure 5.1)	Footslopes, hillslopes, low rises, pediments*, rises, saline stony plains, scarps, stony limestone plains, stony plains	Coolgardie, Eundynie, Graves, Hampton, Jaurdi, Jimberlana, Kanandah, Kurrawang, Lawrence, Moriarty, Quartzitehill, Widgiemooltha, Woolibar, Yandamurrina; minor group in Kanowna, Latimore
Calcareous very shallow soil (Like Calcareous stony soil but shallower)	Soil is shallower than 30 cm over rock; most of the soil is calcareous; soil texture is usually loam or clay; most commonly occurs on mafic and volcaniclastic basement rock	Calcrete rises, hillcrests, hillslopes, low hills, pediments*, ridges, rises, scarps, stony limestone plains	Coolgardie, Eundynie, Gnamma, Graves, Hampton, Jaurdi, Jimberlana, Kanandah, Kurrawang, Lawrence, Moriarty, Noganyer
Stony soil (Like Very shallow soil but deeper)	Soil is deeper than 30 cm, contains many gravels and stones throughout the profile depth, and is not calcareous	Hillcrests, hillslopes, low hills, low rises, pediments*, ridges, tors	Balladonia, Bandy, Binneringie, Bungalbin, Dryandra, Graves, Greenmount, Jaurdi, Jimberlana, Kartukartunga, Lawrence, Marda, Quartzitehill, Sedgeman, Widgiemooltha, Yandamurrina, Zed
Very shallow soil (Like Stony soil but shallower)	Soil is shallower than 30 cm and is not calcareous; unweathered basement rock underlies the soil	Breakaways, granite pavements, gritty-surfaced plains, hillcrests, hillslopes, low rises, pediments*, ridges, tors	Balladonia, Bandy, Bevon, Bungalbin, Greenmount, Hampton, Ironcap, Jaurdi, Jimberlana, Kurrawang, Lawrence, Sedgeman, Symons, Wyralinu, Yandamurrina
Very shallow soil over calcrete	Soil is shallower than 30 cm and overlies calcrete hardpan, and outcrops of calcrete hardpan without any soil; usually underlain by unconsolidated regolith; soil matrix is usually calcareous and loam or clay texture	Calcrete rises, stony limestone plains	Kanandah, Kurrawang, Yandamurrina

(continued)

Table 5.4 (continued): Summary of soil supergroup Shallow, rocky or stony soils

WA Soil Group	Description	Common landforms	Common land systems
Very shallow soil over ferricrete hardpan (Like shallow sandy gravel and shallow loamy gravel [Table 5.3] but shallower)	Soil is shallower than 30 cm and overlies ferricrete hardpan, and outcrops of ferricrete hardpan without any soil; usually underlain by unconsolidated regolith; soil matrix is usually acid to neutral, and sand or loam texture	Breakaways, hillcrests, hillslopes, low rises, ridges	Bevon, Bungalbin, Cundlegum, Dryandra, Euchre, Greenmount, Helena, Hyden, Illaara, Ironcap, Latimore, Marda, Monger; minor group in Bannar
Very shallow soil over hardpan (Like Red–brown hard shallow loam [Table 5.10] but shallower)	Soil is shallower than 30 cm and overlies silcrete hardpan, and outcrops of silcrete hardpan without any soil; usually underlain by unconsolidated regolith; soil matrix can be acid to alkaline, and sand or loam texture is most common	Breakaways, footslopes, hardpan plains, low rises	Euchre, Gransal, Helag

* Pediments are equivalent to 'gritty-surfaced and stony plains' identified in land systems first described in other rangelands inventory reports.

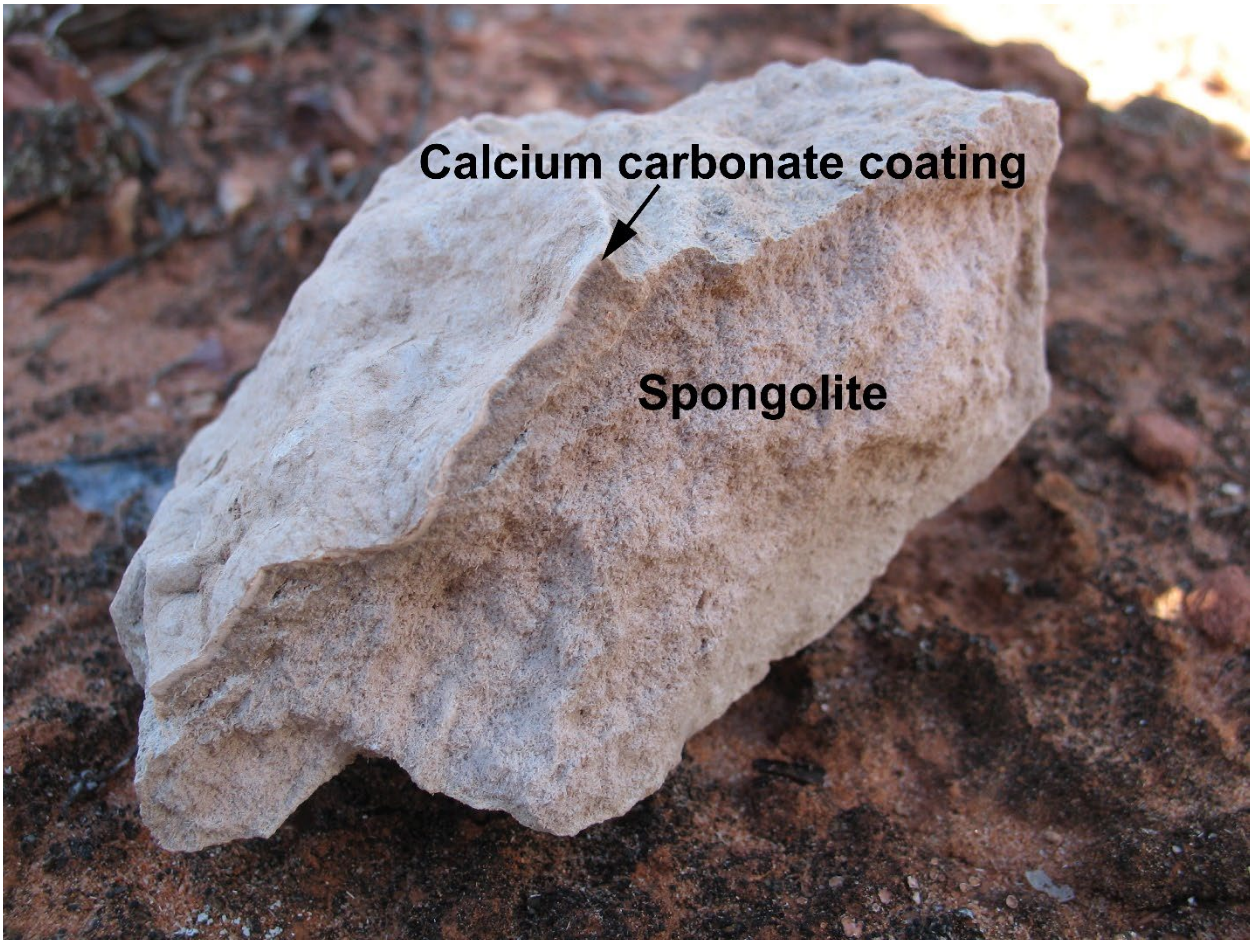


Figure 5.1: The unusual example of Calcareous stony soil from Eundynie land system, where the spongolite parent material has been coated by calcium carbonate of biological origin; the calcium carbonate is visible as a rind coating the highly permeable spongolite

Table 5.5: Summary of soil supergroup Shallow sand soils

WA Soil Group	Description	Common landforms	Common land systems
Ironstone gravelly shallow sand (Rare soil)	Soil is sandy and has an ironstone gravel layer that starts below 15 cm and rock or a ferricrete hardpan is evident within 30–80 cm*	Not common in any landforms	Marmion; *expected in Cundlegum*
Red shallow sand	Soil is sandy and mostly red, over hardpan or rock evident within 30–80 cm (rock does not include limestone)	Footslopes, gravelly sandsheets, gritty-surfaced plains, low rises, pediments, pediplains#, sandplains, sandsheets	Balladonia, Bandy, Charlina, Cundlegum, Kirgella, Kwelkan, Marmion, Norie, Sedgeman, Wallaroo, Yandamurrina
Yellow–brown shallow sand (Rare soil)	Soil is sandy and mostly yellow or brown, over hardpan or rock evident within 30–80 cm (rock does not include limestone)	Not common in any landforms	Joseph, Norie

* Gravel layer is a soil layer containing greater than 20% gravels by visual estimation and is at least 20 cm deep.

\# Pediments and pediplains are equivalent to 'gritty-surfaced and stony plains' described in other rangelands inventory reports.

Shallow sand over a granitic pavement supporting a dense mat of *Borya constricta* (resurrection plant) in the Sedgeman land system

Table 5.6: Summary of soil supergroup Sandy duplex soils

WA Soil Group	Description	Common landforms	Common land systems
Acid sandy duplex	Soil with a sandy topsoil (often has a gritty surface) over a texture contrast to a strongly acid clay subsoil; topsoil is usually acid; soil forms on deeply weathered regolith	Breakaway footslopes, crests and rises, footslopes	Cundlegum, Euchre, Gransal, Ironcap, Monger
Alkaline grey shallow sandy duplex	Soil with a grey or pale sandy topsoil less than 30 cm thick over a texture contrast to an alkaline clay subsoil	Alluvial plains, loamy plains, lunettes, playa plains, sandsheets, sandy banks, undulating plains	Dundas, Halbert, Hann, Lagan, Salmon Gums
Alkaline red deep sandy duplex	Soil with a red sandy topsoil 30–80 cm thick over a texture contrast to an alkaline clay subsoil	Alluvial plains, dunes, lake or swamp margins, lunettes, sandy banks	Carnegie, Emu, Lefroy, Rowles
Alkaline red shallow sandy duplex	Soil with a red sandy topsoil less than 30 cm thick over a texture contrast to an alkaline clay subsoil	Alluvial plains, saline plains	Carnegie, Emu, Garratt, Lefroy, Wangine
Alkaline yellow–brown deep sandy duplex	Soil with a yellow or brown sandy topsoil 30–80 cm thick over a texture contrast to an alkaline clay subsoil; occasionally grey	Low rises, undulating plains, sandsheets	Buraminya, Halbert, Holland, Manning
Alkaline yellow–brown shallow sandy duplex	Soil with a yellow or brown sandy topsoil less than 30 cm thick over a texture contrast to an alkaline clay subsoil	Drainage foci, drainage tracts, low rises, lunettes, playa plains, sandsheets, sandy banks, undulating plains	Buraminya, Cheriton, Forrestania, Hann, Hope South, Moorebar, Newdegate, Sharpe
Grey deep sandy duplex	Soil with a grey or pale sandy topsoil 30–80 cm thick over a texture contrast to a clay subsoil that is not alkaline	Undulating plains, sandsheets	Buraminya, Halbert, Hann, Newdegate
Grey shallow sandy duplex	Soil with a grey or pale sandy topsoil less than 30 cm thick over a texture contrast to a clay subsoil that is not alkaline	Undulating plains, sandsheets	Buraminya, Halbert, Hann, Newdegate
Red shallow sandy duplex	Soil with a red sandy topsoil less than 30 cm thick over a texture contrast to a clay subsoil that is not alkaline	Alluvial plains, footslopes, gritty-surfaced plains, saline stony plains	Cundlegum, Garratt, Gransal
Yellow–brown deep sandy duplex	Soil with a yellow or brown sandy topsoil 30–80 cm thick over texture contrast to a clay subsoil that is not alkaline	Drainage tracts, low rises, lunettes, sandplains, sandsheets, swales	Cronin, Forrestania
Yellow–brown shallow sandy duplex	Soil with a yellow or brown sandy topsoil less than 30 cm thick over a texture contrast to clay subsoil that is not alkaline	Drainage tracts, undulating plains	Ironcap, Joseph

Table 5.7: Summary of soil supergroup Sandy earth soils

WA Soil Group	Description	Common landforms	Common land systems
Calcareous gravelly sandy earth	Soil with a sandy topsoil that grades to a heavier subsoil (sandy loam or heavier) by 80 cm, is calcareous within 30 cm, and has a calcareous gravel layer*	Calcareous sandsheets, loamy plains, lunettes, sandsheets, sandy banks	Erayinia, Gumland, Lakeside, Wangine, Yandamurrina, Yardina, Zanthus
Calcareous sandy earth (Includes gypsic variant)	Soil with a sandy topsoil that grades to a heavier subsoil (sandy loam or heavier) by 80 cm, and is calcareous within 30 cm; gypsum is a major component of the gypsic variant	Alluvial plains, dunes, lunettes, sandsheets, sandy banks	Carnegie, Cheriton, Cronin, Deadman, Halbert, Holland, Hope, Hopeside, Lakeside, Lefroy, Ponton, Sharpe
Calcareous shallow sandy earth	Soil with a sandy topsoil that grades to a heavier subsoil (sandy loam or heavier) by 80 cm, is calcareous within 30 cm, and has a hardpan within 80 cm	Footslopes, riseslopes	Binneringie, Gundockerta, Yandamurrina
Ironstone gravelly acid sandy earth (Rare soil)	Soil with a strongly acid sandy topsoil that grades to a heavier subsoil (sandy loam or heavier) by 80 cm and has an ironstone gravel layer*	Not common in any landforms	Wallaroo
Red sandy earth	Soil with a red sandy topsoil that grades to a heavier subsoil (sandy loam or heavier) by 80 cm; soil is not strongly acid or calcareous	Alluvial plains, calcareous earthy plains, creeklines, dunes, loamy plains, loamy plains, lunettes, sandplains, sandsheets, sandy banks	Carnegie, Cundeelee, Deadman, Kirgella, Lakeside, Marmion, Ponton, Wangine, Yardina, Yowie
Shallow sandy earth (Rare soil)	Soil with a sandy topsoil that grades to a heavier subsoil (sandy loam or heavier) and has rock or hardpan within 80 cm	Not common in any landforms; *expected on footslopes and low rises*	Bandy; *expected in Sedgeman, Wallaroo*
Yellow sandy earth (Rare soil)	Soil with a yellow sandy topsoil that grades to a heavier subsoil (sandy loam or heavier) by 80 cm; soil is not strongly acid or calcareous	Not common in any landforms; *expected on sandsheets*	Joseph

* Gravel layer is a soil layer containing greater than 20% gravels by visual estimation and is at least 20 cm deep.

Table 5.8: Summary of soil supergroup Deep sand soils

WA Soil Group	Description	Common landforms	Common land systems
Brown deep sand	Brown sand that continues to more than 80 cm	Colluvial slopes, drainage foci	Hann, Kartukartunga, Yardina
Calcareous deep sand	Sand that becomes calcareous within 30 cm and continues to more than 80 cm	Sandsheets	Lakeside
Calcareous gravelly deep sand	Sand that becomes calcareous within 30 cm, continues to more than 80 cm and has a calcareous gravel layer that starts after 15 cm and within 80 cm*	Calcrete platforms, sandsheets, sandy banks	Frasershear, Lakeside
Ironstone gravelly coloured deep sand	Yellow, red or brown sand that continues to more than 80 cm and has an ironstone gravel layer that starts after 15 cm and within 80 cm*	Sandplains, gravelly sandsheets	Bannar, Hyden, Joseph
Ironstone gravelly pale deep sand	Pale or grey sand that continues to more than 80 cm and has an ironstone gravel layer that starts after 15 cm and within 80 cm	Lunettes, sandplains, sandsheets, undulating plains	*Expected in Buraminya, Halbert, Hann, Newdegate,*
Pale deep sand	Pale or grey sand that continues to more than 80 cm	Lunettes, sandplains, sandsheets, undulating plains	Hann; *expected in Buraminya, Halbert, Newdegate, Sharpe*
Red deep sand	Red sand that continues to more than 80 cm	Alluvial plains, dunes, gritty-surfaced plains, low rises, lunettes, sandplains, sandsheets, sandy banks	Carnegie, Deadman, Kirgella, Lakeside, Marmion, Pindar, Ponton, Yowie
Yellow deep sand	Yellow sand that continues to more than 80 cm	Dunes, interdunal swales, lunettes, sandplains, sandsheets, undulating plains	Bannar, Buraminya, Cheriton, Forrestania, Halbert, Hann, Holland, Hyden, Joseph, Newdegate, Sharpe, Victoria

* Gravel layer is a soil layer containing greater than 20% gravels by visual estimation and is at least 20 cm deep.

Crest of a sand dune consisting of Yellow deep sand in the Victoria land system

Table 5.9: Summary of soil supergroup Clay soils

WA Soil Group	Description	Common landforms	Common land systems
Friable non-cracking clay	Clay that is more than 80 cm deep and has moderate structure without deep cracks	Alluvial fans, alluvial plains, calcrete plains, calcrete rises, closed depressions, drainage foci, drainage tracts, saline stony plains, swamps	Caiguna, Cowalinya, Cundeelee, Dunnsville, Rowles, Woorbla; minor group in Doney
Hard cracking clay	Clay that is more than 80 cm deep and has strong structure including deep cracks and a hard surface	Alluvial plains, drainage foci, drainage tracts, valley flats, valley floors	Bunyip, Hope South, Rowles, Symons, Yardilla
Hard non-cracking clay	Poorly structured clay that is more than 80 cm deep	Alluvial fans, drainage tracts, playa beds, swamps, valley flats	Cronin, Salmon Gums; minor group in Erayinia
Self-mulching cracking clay	Clay that is more than 80 cm deep and has strong structure including deep cracks and a self-mulching fine surface structure	Alluvial plains, drainage foci, drainage tracts, footslopes, swamps, valley flats	Bunyip, Coolgardie, Cronin, Doney, Emu, Gnamma, Hope South, Marda, Rowles, Symons, Woolibar
Shallow cracking clay	Clay that is 80 cm deep or shallower and has strong structure including deep cracks. Rock is present within 80 cm	Drainage foci, footslopes, gilgai plains, valley flats	Coolgardie, Gnamma, Woolibar, Yandamurrina
Shallow non-cracking clay	Clay that is 80 cm deep or shallower, without strong structure. Rock is present within 80 cm	Drainage tracts, loamy plains, low hills, low rises, saline stony plains, stony plains	Euchre, Gundockerta, Widgiemooltha

Hard cracking clay soil on a gilgai plain supporting *Maireana pyramidata* (sago bush) shrubland in the Bunyip land system

Table 5.10: Summary of soil supergroup Shallow loam soils

WA Soil Group	Description	Common landforms	Common land systems
Calcareous gravelly shallow loam	Loamy soil greater than 30 cm deep with calcareous matrix, a calcareous gravel layer, and a calcrete hardpan evident within 80 cm	Calcrete platforms, calcrete rises, colluvial slopes, footslopes, loamy plains, low hills, low rises, pediments, pediplains*, rises, scarps, stony plains	Charlina, Deadman, Dundas, Eundynie, Gnamma, Gundockerta, Harms, Helag, Johnston, Kurrawang, Marda, Monger, Moriarty, Noondoonia, Nyanga, Symons, Yardilla; minor group in Cheriton, Coolgardie
Calcareous shallow loam	Loamy soil greater than 30 cm deep with a loamy texture, a calcareous matrix, and rock or a hardpan evident within 80 cm	Calcrete plains, calcrete platforms, calcrete rises, footslopes, hillcrests, hillslopes, loamy plains (sometimes with overlying eolian sand or ironstone lag), low rises, pediments, pediplains*, scarps, stony limestone plains, stony plains, valley flats, valley floors	Bunyip, Caiguna, Charlina, Deadman, Euchre, Frasershear, Gnamma, Graves, Greenmount, Gumbelt, Gundockerta, Illaara, Jackson, Kanandah, Kurrawang, Lawrence, Marda, Noganyer, Symons, Widgiemooltha, Woolibar, Wyralinu, Zanthus; minor group in Cheriton
Limestone shallow loam	Loamy soil greater than 30 cm deep with a neutral or acid matrix over limestone rock evident within 80 cm	Gritty-surfaced plains	Balladonia
Red–brown hardpan shallow loam	Loamy soil greater than 30 cm deep with a red–brown (siliceous) hardpan evident within 80 cm	Alluvial plains, hardpan plains, gritty-surfaced plains, loamy plains, loamy plains with ironstone lag, low rises, pavements, pediments*	Bandy, Bunyip, Cundeelee, Deadman, Erayinia, Euchre, Gransal, Gundockerta, Helag, Kirgella, Kwelkan, Manning, Norie, Pindar, Tealtoo, Yowie
Red shallow loam	Red loamy soil greater than 30 cm deep with rock evident within 80 cm	Footslopes, gritty-surfaced plains, loamy plains, low rises, pavements, pediments, pediplains*, stony plains	Balladonia, Bandy, Binneringie, Bungalbin, Charlina, Dryandra, Euchre, Gransal, Helena, Jackson, Johnston, Kwelkan, Marda, Norie, Sedgeman, Yandamurrina, Zed; minor group in Erayinia

* Pediments and pediplains are equivalent to 'gritty-surfaced and stony plains' identified in land systems first described in other rangeland inventory reports.

Calcareous gravelly shallow loam on a hillslope in the Graves land system

Table 5.11: Summary of soil supergroup Loamy duplex soils

WA Soil Group	Description	Common landforms	Common land systems
Alkaline grey deep loamy duplex (Likely to be present; rare soil)	*Soil with a grey loamy topsoil greater than 30 cm deep over a texture contrast to an alkaline clay subsoil evident within 80 cm*	*Not common in any landforms*	*Expected in Erayinia, Gumland, Kurrawang, Woolibar*
Alkaline grey shallow loamy duplex (Likely to be present; like Alkaline yellow–brown shallow loamy duplex)	*Soil with a grey loamy topsoil over a texture contrast to an alkaline clay subsoil evident within 30 cm*	*Alluvial plains, low rises, saline alluvial plains, undulating plains*	*Expected in Buraminya, Burdett, Moorebar*
Alkaline red deep loamy duplex	Soil with a red loamy topsoil greater than 30 cm deep over a texture contrast to an alkaline clay subsoil evident within 80 cm	Alluvial plains, footslopes, loamy plains	Bunyip, Perilya, Wangine
Alkaline red shallow loamy duplex	Soil with a red loamy topsoil over a texture contrast to alkaline clay subsoil evident within 30 cm	Alluvial plains, closed depressions, colluvial slopes, drainage foci, drainage tracts, footslopes, hillslopes, loamy plains, low rises, stony plains, valley floors	Bunyip, Doney, Garratt, Gransal, Graves, Greenmount, Gumland, Gundockerta, Johnston, Lake Deborah, Noondoonia, Perilya, Woolibar, Woorbla, Wyralinu, Yardilla
Alkaline yellow–brown shallow loamy duplex	Soil with a yellow or brown loamy topsoil over a texture contrast to alkaline clay subsoil evident within 30 cm	Drainage tracts, footslopes, hillslopes, low rises, stony plains, undulating plains, valley flats	Buraminya, Burdett, Cronin, Forrestania, Holland, Jimberlana, Noganyer
Red deep loamy duplex (Rare soil)	Soil with a red loamy topsoil greater than 30 cm deep over a texture contrast to neutral clay subsoil evident within 80 cm	Drainage tracts, valley floors	Lakeside, Woolibar
Red shallow loamy duplex	Soil with a red loamy topsoil over a texture contrast to neutral clay subsoil evident within 30 cm	Drainage tracts, gritty-surfaced plains, loamy plains, low rises	Cundeelee, Gransal
Yellow–brown shallow loamy duplex (Rare soil)	Soil with a yellow or brown loamy topsoil over a texture contrast to neutral clay subsoil evident within 30 cm	Drainage tracts	Forrestania

Table 5.12: Summary of soil supergroup Loamy earth soils

WA Soil Group	Description	Common landforms	Common land systems
Calcareous clay loam	Soil with a loamy topsoil that grades to clay within 30 cm and is mostly calcareous to 80 cm	Alluvial plains, drainage tracts, footslopes, loamy plains, loamy plains with ironstone lag, pediplains, valley floors	Charlina, Coolgardie, Gnamma, Graves, Gumland, Lake Deborah, Perilya, Symons
Calcareous gravelly loamy earth	Soil with a loamy topsoil that grades to clay within 30 cm, is mostly calcareous to 80 cm and has a calcareous gravel layer*	Alluvial plains, calcrete plains, calcrete rises, footslopes, loamy plains, loamy plains overlain by eolian sand, low rises, playa plains	Caiguna, Charlina, Coolgardie, Cowalinya, Deadman, Doney, Dundas, Dunnsville, Eundynie, Gumbelt, Harms, Hope, Lake Deborah, Monger, Noondoonia, Sharpe, Woolibar, Zanthus
Calcareous loamy earth; (rarely includes gypsic variant)	Soil with a loamy topsoil that is deeper than 30 cm thick, may grade to a clay texture by 80 cm and is mostly calcareous; gypsum is present and may be a major component of the gypsic variant	Alluvial plains, calcrete plains, calcrete rises, closed depressions, colluvial slopes, drainage tracts, footslopes, hillslopes, loamy plains, loamy plains overlain by eolian sand, loamy plains with ironstone lag, low rises, playa plains, stony plains, undulating plains, valley flats, wide drainage tracts	Caiguna, Charlina, Coolgardie, Cowalinya, Deadman, Doney, Dundas, Dunnsville, Erayinia, Eundynie, Forrestania, Frasershear, Garratt, Graves, Greenmount, Gumbelt, Gumland, Harms, Helag, Hope, Hope South, Hopeside, Illaara, Jaurdi, Johnston, Kurrawang, Lake Deborah, Lakeside, Monger, Moorebar, Moriarty, Noganyer, Nyanga, Perilya, Salmon Gums, Sharpe, Woolibar, Woorbla, Yardilla, Zanthus
Heavy loamy earth	Soil with a loamy topsoil that grades to clay within 30 cm and is not calcareous	Alluvial plains, drainage tracts, loamy plains	Kanowna Moriarty, Perilya
Red loamy earth	Soil with a red loamy topsoil that is deeper than 30 cm thick, may grade to a clay texture by 80 cm and is not calcareous	Alluvial plains, drainage tracts, footslopes, loamy plains, loamy plains with ironstone lag, low rises	Bannar, Dunnsville, Erayinia, Garratt, Gumland, Harms, Helag, Illaara, Latimore, Pindar, Sedgeman, Tealtoo, Yowie
Yellow–brown loamy earth (Rare soil)	Soil with a yellow or brown loamy topsoil that is deeper than 30 cm thick, may grade to a clay texture by 80 cm and is not calcareous	Drainage tracts	Hope

* Gravel layer is a soil layer containing greater than 20% gravels by visual estimation and is at least 20 cm deep.

Characteristics of the major soils

This section summarises the attributes of soils of the survey area. We describe 43 soil types, classify them using WA Soil Groups and the ASC, and identify their common land systems and landforms. We also define the key characteristics for soil and land management using the methods and definitions of van Gool et al. (2005). We simplified the list to 17 soil suites by grouping WA Soil Groups with genetic and morphological similarities, which can be managed uniformly on a broad scale. Throughout this section we outline some soil processes that are further explained in the Soil formation section.

Soil suite 1: Saline soils of the salt lakes

This suite comprises Salt lake soil, Saline wet soil and Saline soil. The soils are dominant in lake beds and the margins of salt lakes and playas in the Burdett, Carnegie, Cheriton, Halbert, Hope, Lagan, Lake Deborah, Lefroy, Ponton, Sharpe, Victoria and Yardina land systems.

Salt lake soil is a depositional landform rather than a true soil because it supports no plant life. It is hypersaline, highly alkaline and waterlogged, high in chloride, sulfate and carbonate salts and has variable clay, silt and sand contents. Two sites were described.

Saline wet soil and Saline soil are both hypersaline, have salt crusts and ‘fluffy’ saline surfaces, and support sparse halophytic vegetation. Nine sites were described. They have variable profiles, usually with a thin veneer of sand or silty loam above the saline lake bed or other saline deposits. Saline wet soil and Saline soil form at the margins of salt lakes and on raised, windblown deposits within the lake beds.

Saline soils also form as a result of recent accumulations of salt within pre-existing soil profiles. They usually occur in low-lying landforms. Saline soils have variable profiles because they can form in the entire range of soil types in the survey area. However, they most commonly occur in alluvial plains and drainage depressions, and so are often alkaline red loamy duplex or red clay soil profiles. Alternatively, in areas with salt accumulation from weathered bedrock affected by salinity, such as near salt lakes, they can form on skeletal soils.

These land surfaces and materials are not described further in this bulletin because they lack vegetation and so have no grazing value. For more information, see Schoknecht and Pathan (2013).

Soil suite 2: Gypsiferous soils

This suite is a minor soil type comprising 2 soils that have in common being formed on an accumulation of wind-deposited gypsum and classified as the gypsiferous phase of Calcareous sandy earth or, rarely, Calcareous loamy earth (Table 5.13). They were identified in the Carnegie, Lefroy, Victoria and Yardina land systems. They are known from other surveys to occur in Halbert, Hope and Lagan land systems. They are expected to also occur on lunettes of Burdett, Cheriton, Hopeside, Lake Deborah, Lakeside, Ponton and Sharpe land systems. Gypsum deposits form where platforms and dunes of salt lakes become raised high enough above the lake bed for rain to leach some salts, allowing halophytic plants to establish and collect windblown gypsum-rich dust from the lake beds. These deposits are highly saline, alkaline and support low densities of halophytic plants. Although the gypsum is easily blown from the lake beds to form deposits, they quickly become immobilised when rain falls on them and slightly dissolves the gypsum that reprecipitates as a coherent crust, subsequently protecting it from wind erosion. However, if the crust is destroyed by stock or vehicles, these soils can be eroded by wind.

Table 5.13: Summary of attributes of gypsiferous Calcareous sandy earth and Calcareous loamy earth soils

Attribute	Description
Australian Soil Classification	Hypergypsic Rudosol, Hypergypsic Calcarosol
Land systems	Burdett, Carnegie, Cheriton, Halbert, Hope, Hopeside, Lagan, Lake Deborah, Lefroy, Ponton, Sharpe, Victoria, Yardina
Landforms	Kopi dunes, lake beds, low dunes, saline plains
Soil texture notes	Layered deposits of fine gypsum crystals with fine sand or clay lenses
Soil colour	Greyish brown to brownish yellow or yellowish brown
Soil depth	Very deep (>150 cm)
Structure and fabric	Apedal, earthy
Soil surface condition	Crusted
Topsoil and subsoil pH rating (range)	Strongly alkaline (>8.5)
Salinity rating (EC_e)	Highly to extremely saline (>800 mS/m)
Soil permeability	Moderately rapid
Available water storage	Low (because of salinity)
Wind and water erosion hazard	Low

Note: Data is based on 5 sites. The 2 soil types are grouped because both are gypsiferous.

Soil suite 3: Calcareous soils with deep loamy profiles

This suite is ubiquitous throughout the east and dominant across much of the survey area. It was described from 81 sites. It comprises Calcareous loamy earth, Calcareous gravelly loamy earth and Calcareous clay loam (Table 5.14, Table 5.15, Table 5.16). It is related to soil suite 4 because it has a similar texture profile and forms in similar landforms. It is also related to soil suite 5 because it has similar calcareous chemistry and a slightly more clayey texture profile. These soils mostly occupy loamy plains and footslopes, but may occur on drainage areas and rises, and occasionally on hillslopes and dunes. Figure 5.2 shows a typical example of calcareous soils in the south-east (compare to Figure 5.3 that shows a suite 5 soil common to the Dundas Zone). The 3 component soils form a continuum and differences in classification relate to the grade of texture and the prominence of calcareous concretions. The soils range from pale brown or grey to a dark red and are highly alkaline from the surface or near-surface.

Calcareous loamy earth soils in the Woolibar and Coolgardie land systems have high salt stores and are more prone to erosion by wind and water than other calcareous loamy earth soils. Erosion is common on these soils in the Woolibar land system because their surfaces lack significant stony mantles. In contrast, otherwise similar soils in the Coolgardie land system have stony mantles that protect against erosion, and so erosion mostly starts where the stony mantles have been removed.

The Calcareous gravelly loamy earth has 2 configurations, designated ‘type 1’ and ‘type 2’ in Table 5.15. Type 1 is a deep soil that forms on depositional landforms, mostly footslopes and plains, and type 2 is a shallow soil that forms from basement rock on low rises and pediments. The shallow variant usually has some rock at depth and occasionally has a stony mantle.

The Calcareous clay loam has a heavy texture and high clay content relative to the others in this suite and it has 2 configurations, designated ‘type 1’ and ‘type 2’ in Table 5.16. Type 1 is a deep soil that forms on depositional landforms, mostly alluvial plains, valley floors and drainage tracts, and is often saline with gypsum at depth. In contrast, type 2 is a shallow soil that is not saline and forms from basement rock on crests, rises and pediments. The shallow variant usually has some rock at depth and occasionally has a stony mantle.

Table 5.14: Summary of attributes of Calcareous loamy earth

Attribute	Description
Australian Soil Classification	Hypercalcic Calcarosol
Land systems	Charlina, Coolgardie, Cowalinya, Doney, Deadman, Dundas, Eundynie, Frasershear, Garratt, Graves, Gumbelt, Gumland, Gundockerta, Helag, Hopeside, Illaara, Jaurdi, Joseph, Kanowna, Kurrawang, Noondoonia, Perilya, Woolibar, Yardina, Zanthus
Landforms	Loamy plains, lower footslopes
Soil texture notes	Silty loam or sandy clay loam grading to silty clay or medium clay
Soil colour	Brown to yellowish brown
Soil depth	Very deep (>150 cm)
Structure and fabric	Apedal, earthy
Soil surface condition	Crusted or soft; a biological crust is commonly present
Topsoil pH rating (range)	Moderately alkaline (8.0–8.5)
Subsoil pH rating (range)	Strongly alkaline (9.0–9.5)
Salinity rating (EC_e)	Not saline (<200 mS/m); occasionally slightly to moderately saline (200–800 mS/m)
Soil permeability	Moderately slow to moderate
Available water storage	High
Wind erosion hazard	High
Water erosion hazard	Low

Note: Data is based on 46 sites.

Calcareous loamy earth supporting *Casuarina pauper* (black oak) woodland in the Yardina land system

Table 5.15: Summary of attributes of Calcareous gravelly loamy earth

Attribute	Description
Australian Soil Classification	Supracalcic Calcarosol, Lithocalcic Calcarosol, Calcareous Hypersalic Rudosol, Haplic Supracalcic Red Kandosol
Land systems	Type 1: Cheriton, Cowalinya, Doney, Dundas, Gumbelt, Sharpe, Woolibar, Woorbla *Expected in Halbert, Hope, Lagan, Lake Deborah, Lakeside, Lefroy* Type 2: Coolgardie, Dundas, Dunnsville, Gundockerta, Johnston, Monger, Woolibar
Landforms	Type 1: Loamy plains, low rises Type 2: Low rises, pediments*
Soil texture and coarse fragments notes	Silty loam or sandy clay loam grading to silty clay to medium clay; common to many calcareous concretions
Soil colour	Brown or strong brown to reddish brown
Soil depth	Very deep (>150 cm)
Structure and fabric	Apedal, earthy
Soil surface condition	Crusted or soft, common biological crust
Topsoil pH rating (range)	Moderately alkaline (8.0–8.5)
Subsoil pH rating (range)	Strongly alkaline (9.0–9.5)
Salinity rating (EC_e)	Not saline to slightly saline (<200–400 mS/m)
Soil permeability	Moderate
Available water storage	Moderate
Wind erosion hazard	High
Water erosion hazard	Low

* Pediments are equivalent to ‘gritty-surfaced and stony plains’ identified in land systems first described in other rangelands inventory reports.

Note: Data is based on 25 sites.

Calcareous gravelly loamy earth on a low rise supporting *Casuarina pauper* (black oak) woodland in the Illaara land system

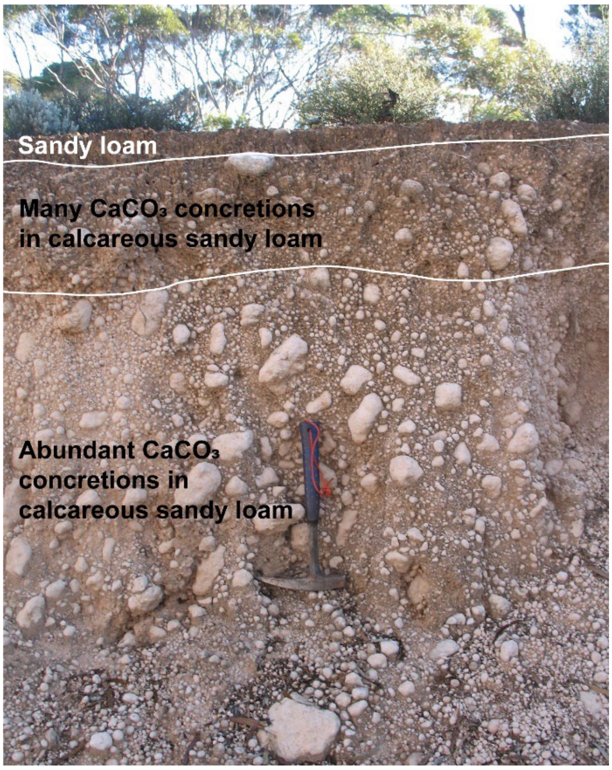


Figure 5.2: Calcareous gravelly loamy earth soil near Balladonia roadhouse on a loamy plain in the Gumbelt land system. This soil is from the suite of calcareous soils that comprises the most common soils of the area. Although this soil profile classifies as having a loamy texture, it is a light sandy loam, and so is very similar to the calcareous gravelly sandy earth

Table 5.16: Summary of attributes of Calcareous clay loam

Attribute	Description
Australian Soil Classification	Hypercalcic Calcarosol
Land systems	Type 1: Coolgardie, Gumland, Kanowna, Woolibar (deep, saline and sometimes gypsiferous at depth) Type 2: Graves, Johnston, Symons (rocky at depth, not saline, sometimes with stony mantle)
Landforms	Type 1: Plains (alluvial, loamy or saline) Type 2: Hillcrests, pediments*, rise slopes
Soil texture notes	Silty clay loam grading to medium clay or heavy clay
Soil colour	Reddish brown to yellowish red
Soil depth	Very deep (>150 cm)
Structure and fabric	Apedal, earthy or massive throughout
Soil surface condition	Firm, crusted, sparse biological crust
Topsoil pH rating (range)	Moderately alkaline (8.0–8.5)
Subsoil pH rating (range)	Strongly alkaline (9.0–9.5)
Salinity rating (EC_e)	Not saline to moderately saline (<200–800 mS/m)
Soil permeability	Slow to moderately slow
Available water storage	Moderate to high
Wind erosion hazard	Moderate
Water erosion hazard	Low

* Pediments are equivalent to ‘gritty-surfaced and stony plains’ identified in land systems first described in other rangelands inventory reports.

Note: Data is based on 10 sites.

Soil suite 4: Deep loamy earth soils with a neutral to acid pH in the subsoil

This suite of soils is uniform, comprising only Red loamy earth (Table 5.17). It was described from 25 sites. Deep loamy earth soils are not calcareous for most of their depth. However, they usually become calcareous in the lower part of the profile, sometimes have calcareous concretions at depth and may be underlain by calcrete hardpan, silcrete hardpan or a red–brown hardpan (which is often cemented by silcrete, iron oxides and carbonates). These soils become more prominent further north, partly supplanting Calcareous loamy earth. They tend to form under mixed acacia and eucalypt woodland in the transition zone between IBRA regions. Twenty-five sites were described, mostly on plains and drainage depressions in Doney, Gumland, Helag, Illaara, Moorebar and Pindar land systems. They were identified less often within Bannar, Charlina, Cundlegum, Dundas, Frasershear, Kanowna, Kirgella, Perilya, Rowles and Sedgeman land systems.

In the far south in the Hope land system, we found one example of a similar soil that was yellow–brown instead of the usual red; we did not describe it separately.

This suite of soils is resistant to erosion and has moderate permeability, so rarely generates significant run-off.

Table 5.17: Summary of attributes of Red loamy earth

Attribute	Description
Australian Soil Classification	Red Dermosol
Land systems	Bannar, Charlina, Cundlegum, Doney, Dundas, Frasershear, Gumland, Helag, Hope, Illaara, Kanowna, Kirgella, Moorebar, Pindar, Perilya, Rowles, Sedgeman
Landforms	Alluvial fans, drainage floors, drainage foci, footslopes, gilgai plains, hardpan plains, loamy plains, swamps, valley flats
Soil texture notes	Topsoil is most commonly sandy loam, rarely clay loam Subsoil ranges from sandy clay loam to light clay
Soil colour	Red to dark red
Soil depth	Deep to very deep (>80 cm)
Structure and fabric	Apedal, earthy, or crumb to fine subangular blocky topsoil; earthy or coarse angular blocky subsoil
Soil surface condition	Soft to firm
Topsoil pH rating (range)	Slightly acid to moderately alkaline (5.5–8.0)
Subsoil pH rating (range)	Neutral to moderately alkaline (6.5–8.0), sometimes strongly alkaline (>9.0) in lower subsoil
Salinity rating (EC_e)	Not saline to moderately saline (<200–800 mS/m)
Soil permeability	Moderately slow to moderate
Available water storage	High
Wind and water erosion hazard	Low

Note: Data is based on 25 sites.

Soil suite 5: Calcareous soils with deep sandy profiles

This is a common suite of soils described from 11 sites. It comprises the non-gypsiferous phase of Calcareous sandy earth (the gypsiferous phase is described in soil suite 2), Calcareous gravelly sandy earth, Calcareous deep sand and Calcareous gravelly deep sand.

Sandy calcareous soils are dominant soils forming generally to the south-east and east of salt lakes in sandsheets and sand dunes blown from the lake beds in the Cronin, Holland, Lakeside, Sharpe and Yardina land systems. These soils are also widespread on land systems formed from marine sediments that have eolian reworking, principally Zanthus and the south-eastern portion of the Doney land system within the Dundas Zone, and within the Yandamurrina land system east of Fraser Range.

Dunes closest to the lakes are most prominent and they become more subdued and merge to very gently undulating sandsheets further south-east and east of the lake margins. Dunes close to lake sources are younger deposits. These soils are dominantly Calcareous deep sand and Calcareous sandy earth. They are composed mostly of fine, rounded quartz sand. The dunes retain the highly calcareous chemistry of parent sources because rain that falls on the highly permeable deposits are sufficient to leach soluble salts like chloride and sulfur salts, but the less soluble carbonate salts are retained and concentrated by hydraulic redistribution by the eucalypts that grow on them (see Formation of calcium carbonate concretions section).

Moving further south-east and away from the well-defined dunefields, the landforms become older and more subdued, forming sandsheets. In these locations, the calcium carbonate does not leach away with additional time and rain. Instead, it concentrates deeper in the profile and forms rounded calcareous concretions, the result of biological concentration from a combination of hydraulic redistribution and microbial associates of eucalypts.

This suite is not prone to erosion, except immediately after fire when wind erosion may occur.

Table 5.18: Summary of attributes of Calcareous sandy earth

Attribute	Description
Australian Soil Classification	Hypocalcic Brown Kandosol, Hypocalcic Red Kandosol
Land systems	Cronin, Doney, Dundas, Holland, Lakeside, Sharpe, Yandamurrina, Yardina
Landforms	Dunes, lunettes, sandsheets
Soil texture notes	Clayey sand grading to sandy loam
Soil colour	Red to brown or yellowish brown
Soil depth	Very deep (>150 cm)
Structure and fabric	Apedal, single grain topsoil; apedal, earthy subsoil
Soil surface condition	Loose
Topsoil pH rating (range)	Neutral (6.5–7.5)
Subsoil pH rating (range)	Strongly alkaline (8.5–9.5)
Salinity rating (EC_e)	Not saline (<200 mS/m)
Soil permeability	Moderately rapid
Available water storage	Moderate
Wind erosion hazard	Very high
Water erosion hazard	Low

Note: Data is based on 6 sites.

Table 5.19: Summary of attributes of Calcareous gravelly sandy earth

Attribute	Description
Australian Soil Classification	Supracalcic Brown Kandosol, Regolithic Supracalcic Calcarosol
Land systems	Carnegie, Cronin, Dundas, Holland, Lakeside, Sharpe, Yardina, Zanthus
Landforms	Lunettes, sandsheets
Soil texture and coarse fragments notes	Fine sand grading to fine sandy loam; common to many calcareous concretions
Soil colour	Reddish brown to brown
Soil depth	Very deep (>150 cm)
Structure and fabric	Apedal, single grain
Soil surface condition	Loose
Topsoil pH rating (range)	Neutral (6.5–7.5)
Subsoil pH rating (range)	Strongly alkaline (8.5–9.5)
Salinity rating (EC_e)	Not saline (<200 mS/m)
Soil permeability	Rapid
Available water storage	Low to moderate
Wind erosion hazard	Very high
Water erosion hazard	Low

Note: Data is based on 2 sites.

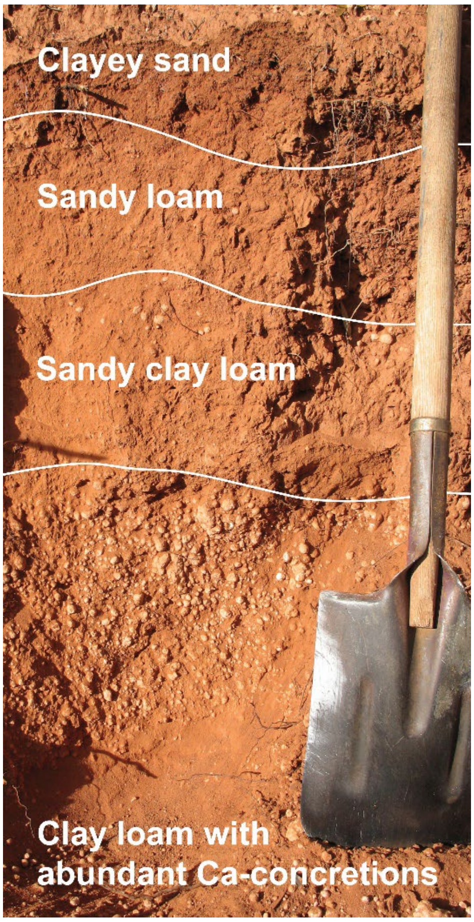


Figure 5.3: Shallow pit of Calcareous gravelly sandy earth with calcareous concretions in the subsoil. This soil is common in the Dundas and Zanthus land systems across the Dundas Zone

Table 5.20: Summary of attributes of Calcareous deep sand

Attribute	Description
Australian Soil Classification	Calcareous Arenic Red-Orthic Tenosol
Land systems	Holland, Lakeside
Landforms	Lunettes, sandsheets
Soil texture notes	Fine sand throughout; occasionally increasing to clayey fine sand at depth
Soil colour	Reddish brown to yellowish red
Soil depth	Very deep (>150 cm)
Structure and fabric	Apedal, single grain
Soil surface condition	Loose
Topsoil pH rating (range)	Neutral (6.5–7.5)
Subsoil pH rating (range)	Strongly alkaline (8.5–9.5)
Salinity rating (EC_e)	Not saline (<200 mS/m)
Soil permeability	Very rapid
Available water storage	Moderate
Wind erosion hazard	Very high
Water erosion hazard	Low

Note: Data is based on 1 site.

Table 5.21: Summary of attributes of Calcareous gravelly deep sand

Attribute	Description
Australian Soil Classification	Supracalcic Arenic Calcenic Tenosol
Land systems	Lakeside
Landforms	Sandsheets
Soil texture and coarse fragments notes	Fine sand throughout; occasionally increasing to clayey fine sand at depth; common to many calcareous concretions
Soil colour	Reddish brown to yellowish red
Soil depth	Very deep (>150 cm)
Structure and fabric	Apedal, single grain
Soil surface condition	Loose
Topsoil pH rating (range)	Neutral (6.5–7.5)
Subsoil pH rating (range)	Strongly alkaline (8.5–9.5)
Salinity rating (EC_e)	Not saline (<200 mS/m)
Soil permeability	Rapid
Available water storage	Low to moderate
Wind erosion hazard	Very high
Water erosion hazard	Low

Note: Data is based on 2 sites.

Soil suite 6: Deep sandy soils with neutral to acid pH

This is a major suite of soils described from 46 sites. These soils are prominent and extensive across the sandplain areas of the Joseph land system in the Youanmi South Zone, Kirgella and Marmion land systems in the Leemans Sandplain and Salinaland Plains zones, and the Victoria land system in the Southern Victoria Desert Zone. They are also present as dune deposits to the south-east of lakes in the south and west of the survey area within the Buraminya, Halbert, Hann, Holland and Lakeside land systems. Two soil types are common: Red deep sand (Table 5.22, Figure 5.4) and Yellow deep sand (Table 5.23, Figure 5.5). Pale deep sand and Brown deep sand are rare and limited to the far south of the survey area (Table 5.24).

Most soil variants are uniform-textured deep quartz sand with acid to neutral soil pH chemistry. Gypsum is absent. Red deep sand forms the sandplain over granitic basement in the north, and Yellow deep sand forms the sandplain over granitic basement in the south-west and on Canning and Officer basin sediments in the east. In the north and east, Red deep sand and Yellow deep sand are both populated by spinifex and *Eucalyptus* species. In contrast, the Yellow deep sand on sandplain over granitic basement in the south-west is populated by proteaceous heath dominated by *Banksia*, *Hakea* and *Grevillea* species. In the far south on the Halbert and Hann land systems, the Yellow deep sand yields to Brown and Pale deep sands formed on marine sediments and eolian deposits and vegetated by mixed Proteaceous–Myrtaceous heath with a eucalypt (mallee) component.

Some deep sands increase in texture at depth and classify as Red or Yellow sandy earth soils (Table 5.25, Figure 5.6). Thirteen such examples were described, and most were located on windblown sandsheets from salt lakes. They generally have an affinity with soil suite 5, calcareous deep sandy soils, but are only calcareous in the deep subsoil, if at all.

Deep sandy soils are prone to wind erosion after wildfire removes the protective vegetation.

Table 5.22: Summary of attributes of Red deep sand

Attribute	Description
Australian Soil Classification	Red-Orthic Tenosol
Land systems	Windblown and sedimentary origins: Victoria, Zanthus Granite-derived: Kirgella, Marmion
Landforms	Dunes, lunettes, sandplains, sandsheets
Soil texture notes	Windblown and sedimentary origins: fine sand Granite-derived: medium sand to clayey sand
Soil colour	Red to dark red
Soil depth	Very deep (>150 cm)
Structure and fabric	Apedal, single grain
Soil surface condition	Loose
Topsoil pH rating (range)	Slightly acid to neutral (5.5–6.5)
Subsoil pH rating (range)	Slightly acid to neutral (5.5–7.5), occasionally becoming moderately alkaline at depth (8.0)
Salinity rating (EC_e)	Not saline (<200 mS/m)
Soil permeability	Rapid to very rapid
Available water storage	Moderate
Wind erosion hazard	Very high
Water erosion hazard	Low

Note: Data is based on 16 sites.

Figure 5.4: Sand quarry in the Marmion land system – note the great depth of Red deep sand as indicated by the road train in the right of the photo

Table 5.23: Summary of attributes of Yellow deep sand

Attribute	Description
Australian Soil Classification	Yellow-Orthic Tenosol
Land systems	Windblown and sedimentary origins: Buraminya, Holland, Lakeside, Victoria, Zanthus Granite-derived: Joseph, Kirgella, Marmion
Landforms	Dunes, lunettes, sandplains, sandsheets
Soil texture notes	Windblown and sedimentary origins: fine sand Granite-derived: medium sand to clayey sand
Soil colour	Brown to brownish yellow
Soil depth	Very deep (>150 cm)
Structure and fabric	Apedal, single grain
Soil surface condition	Loose
Topsoil pH rating (range)	Moderately acid (5.0–5.5)
Subsoil pH rating (range)	Slightly acid to neutral (5.5–7.0)
Salinity rating (EC_e)	Not saline (<200 mS/m)
Soil permeability	Rapid to very rapid
Available water storage	Moderate
Wind erosion hazard	Very high
Water erosion hazard	Low

Note: Data is based on 14 sites.

Figure 5.5: Sand quarry in the Joseph land system – note depth of Yellow deep sand as indicated by the vehicle in the left of the photo

Table 5.24: Pale deep sand and Brown deep sand

Attribute	Description
Australian Soil Classification	Grey-Orthic Tenosol, Brown-Orthic Tenosol
Land systems	Halbert, Hann
Landforms	Dunes, lunettes, sandplains, sandsheets
Soil texture notes	Fine to medium sand
Soil colour	Greyish brown to light grey
Soil depth	Very deep (>150 cm)
Structure and fabric	Apedal, single grain
Soil surface condition	Loose
Topsoil and subsoil pH rating (range)	Slightly acid to neutral (5.5–6.5)
Salinity rating (EC_e)	Not saline (<200 mS/m)
Soil permeability	Rapid to very rapid
Available water storage	Low to moderate
Wind erosion hazard	Very high
Water erosion hazard	Low

Note: Data is based on 3 sites.

Table 5.25: Summary of attributes of Red sandy earth

Attribute	Description
Australian Soil Classification	Red Kandosol, Yellow Kandosol
Land systems	Carnegie, Deadman, Dunnsville, Helag, Joseph, Lake Deborah, Lakeside, Lefroy, Ponton
Landforms	Dunes, loamy plains, lunettes, sandplains, sandsheets, sandy banks, terraces
Soil texture notes	Loamy sand grading to sandy clay loam
Soil colour	Reddish brown or yellowish red grading to red or dark red
Soil depth	Very deep (>150 cm)
Structure and fabric	Apedal, massive throughout
Soil surface condition	Loose to soft
Topsoil pH rating (range)	Moderately acid to slightly acid (5.0–6.0)
Subsoil pH rating (range)	Neutral (6.5–7.5)
Salinity rating (EC_e)	Not saline to slightly saline (<400 mS/m)
Soil permeability	Moderately rapid to rapid
Available water storage	Moderate
Wind erosion hazard	Very high
Water erosion hazard	Low

Note: Data is based on 13 sites.

Figure 5.6: Yellow sandy earth was rarely encountered during the survey (this example was in the Joseph land system); most soils of this profile and pH form were red

Soil suite 7: Sandy duplex soils with neutral to acid pH in the subsoil

This suite comprises a range of soils distinguished by the presence of a sandy topsoil and a distinct and rapid change in texture to a clayey subsoil with little or no accumulation of calcium carbonate. The diverse range present across the survey area is a consequence of the WA Soil Group classification, which uses colour of topsoil and depth of the transition between sandy topsoil and clayey subsoil as primary distinguishing features. We have grouped the range of soils present into acid sandy duplex, shallow sandy duplex (topsoil depth is shallower than 30 cm) and deep sandy duplex (topsoil depth is between 30 and 80 cm). The latter 2 soils occur as 3 colour variants: yellow–brown, red or grey. The most common soil found of these potential combinations is the Yellow–brown shallow sandy duplex (Figure 5.7); deep topsoil greater than 30 cm is uncommon; and topsoils are rarely red or grey.

This is a common suite described from 20 sites. They are common on weathered regolith and in low-lying landforms subjected to salinity, although most have been leached of salts in the upper part of the subsoil. Most soils have sodium attached to clay minerals and are classified as sodic or highly sodic.

The sandy duplex soils on weathered granitic regolith occur in the Bannar, Cundlegum, Euchre, Gransal and Joseph land systems. They are commonly Acid sandy duplex and Yellow–brown deep sandy duplex, and less commonly are Yellow–brown shallow sandy duplex (Table 5.26, Table 5.27, Table 5.28).

Sandy duplex soils occur in low-lying landforms including alluvial plains fringing salt lakes, drainage floors, playas, saline plains and swamps with eucalypt (mallee) woodlands, melaleuca and heath of the Buraminya, Burdett, Carnegie, Cheriton, Cronin, Dundas, Hann, Lakeside, Newdegate, Ponton, Sharpe and Yardina land systems. They are most commonly Yellow–brown shallow sandy duplex and deep sandy duplex (Table 5.28, Figure 5.7). Occasionally they are Red shallow sandy duplex on saline plains of the Carnegie and Gransal land systems and Grey deep sandy duplex on sandsheets in the Hann land system. Other rare sandy duplex soils have been grouped with those described above.

Sandy duplex soils in the south of the survey area can become waterlogged and cause difficulty with trafficability. They are not prone to water erosion unless denuded and saturated. Wind erosion is not significant.

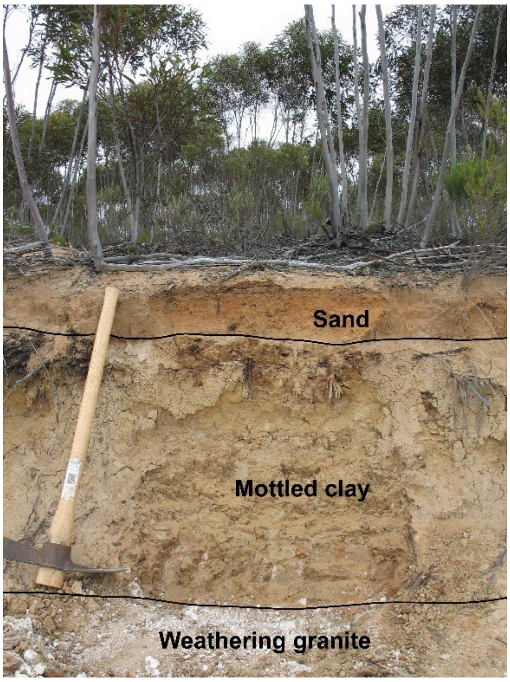


Figure 5.7: Yellow–brown shallow sandy duplex soil in the Newdegate land system

Table 5.26: Summary of attributes of Acid sandy duplex

Attribute	Description
Australian Soil Classification	Brown Kurosol
Land systems	Bannar, Cundlegum, Euchre, Gransal, Joseph
Landforms	Breakaway scarps, breakaway footslopes
Soil texture notes	Sand over light to medium clay
Soil colour	Grey or greyish brown to brown
Soil depth	Shallow to moderate (15–80 cm)
Structure and fabric	Apedal, single grain topsoil; large columnar or prismatic subsoil
Soil surface condition	Loose to soft
Topsoil pH rating (range)	Strongly acid to neutral (4.5–6.5)
Subsoil pH rating (range)	Very strongly acid (<4.5); deep subsoils occasionally become alkaline
Salinity rating (EC_e)	Slightly to highly saline (200–1,600 mS/m)
Soil permeability	Very slow to slow
Available water storage	Very low
Wind erosion hazard	High
Water erosion hazard	Moderate

Note: Data is based on 3 sites.

Table 5.27: Summary of attributes of Yellow–brown deep sandy duplex

Attribute	Description
Australian Soil Classification	Mesonatric or Hypernatric Brown Sodosol
Land systems	Buraminya, Cheriton, Cronin, Dundas, Hann, Lakeside, Newdegate
Landforms	Drainage floors, playas, sandsheets, swamps
Soil texture notes	Medium to coarse loamy sand over light to medium clay
Soil colour	Pale brown or yellowish brown; occasionally strong brown or yellowish red
Soil depth	Moderate (30–80 cm)
Structure and fabric	Apedal, single grain topsoil; large columnar or prismatic subsoil
Soil surface condition	Loose to soft
Topsoil pH rating (range)	Strongly acid to neutral (4.5–6.5)
Subsoil pH rating (range)	Neutral to moderately alkaline (6.0–8.0)
Salinity rating (EC_e)	Not saline to slightly saline (<200–400 mS/m)
Soil permeability	Very slow to slow
Available water storage	Low
Wind erosion hazard	Moderate
Water erosion hazard	Low to very low

Note: Data is based on 5 sites.

Table 5.28: Summary of attributes of Yellow–brown shallow sandy duplex

Attribute	Description
Australian Soil Classification	Mesonatric or Hypernatric Brown Sodosol
Land systems	Buraminya, Cheriton, Cronin, Dundas, Hann, Kartukartunga, Lakeside, Newdegate, Ponton, Yardina
Landforms	Drainage floors, playas, sandsheets, swamps
Soil texture notes	Medium to coarse loamy sand over light to medium clay
Soil colour	Pale brown or yellowish brown; occasionally strong brown or yellowish red
Soil depth	Shallow to moderate (15–80 cm)
Structure and fabric	Apedal, single grain topsoil; large columnar or prismatic subsoil
Soil surface condition	Loose to soft
Topsoil pH rating (range)	Strongly acid to neutral (4.5–6.5)
Subsoil pH rating (range)	Neutral to moderately alkaline (6.0–8.0)
Salinity rating (EC_e)	Not saline to slightly saline (<200–400 mS/m)
Soil permeability	Very slow to slow
Available water storage	Very low
Wind erosion hazard	Moderate
Water erosion hazard	Low

Note: Data is based on 12 sites.

Sandy duplex soil on a low rise supporting mixed eucalypt (mallee) woodland in the Newdegate land system

Soil suite 8: Sandy duplex soils with alkaline pH in the subsoil

This suite comprises a range of soils distinguished by the presence of a sandy topsoil and a distinct and rapid change in texture to a clayey subsoil that is alkaline, often sodic or highly sodic and usually has an accumulation of carbonate minerals at depth. The diverse range is a consequence of the WA Soil Group classification, which uses colour of topsoil and depth of the transition between sandy topsoil and clayey subsoil as primary distinguishing features. The combination of several slightly different colours and a depth threshold of 30 cm between 'shallow' and 'deep' artificially multiplies the range of soils present, even though they may be very similar.

This is a common suite of soils described from 30 sites. These soils commonly occur on depositional, low-lying landforms and are less common on fresh basement rock. Alkaline sandy duplex soils are present in 20 land systems, a much wider range than the acid and neutral sandy duplex soils described in soil suite 6.

Alkaline sandy duplex soils on fresh basement are present in the Buraminya, Dundas, Garratt, Gundockerta, Kurrawang, Sedgeman and Yardilla land systems. They always have shallow sandy topsoils, most commonly Alkaline red shallow sandy duplex, although occasionally can become Alkaline yellow–brown shallow sandy duplex in the south (Table 5.29, Table 5.30).

Alkaline sandy duplex soils mostly occur in low-lying positions. They are most commonly Alkaline red shallow sandy duplex and Alkaline yellow–brown shallow sandy duplex, and occasionally Alkaline red deep sandy duplex and Alkaline yellow–brown deep sandy duplex (Table 5.31, Table 5.32). Other rare alkaline sandy duplex soils have been grouped with those described above.

Table 5.29: Summary of attributes of Alkaline red shallow sandy duplex

Attribute	Description
Australian Soil Classification	Mesonatric or Hypernatric Red Sodosol
Land systems	Buraminya, Carnegie, Deadman, Lefroy, Sedgeman, Yardina
Landforms	Drainage floors, footslopes, loamy plains, playa plains, saline plains, sandsheets, swamps
Soil texture notes	Loamy sand over light to medium clay
Soil colour	Yellowish red to dark red
Soil depth	Shallow to moderate (15–80 cm)
Structure and fabric	Apedal, single grain topsoil; large columnar or prismatic subsoil
Soil surface condition	Soft to firm
Topsoil pH rating (range)	Neutral (6.0–7.0)
Subsoil pH rating (range)	Strongly alkaline (8.5–9.5)
Salinity rating (EC_e)	Not saline to slightly saline (<200–400 mS/m)
Soil permeability	Very slow to slow
Available water storage	Very low to low
Wind erosion hazard	Moderate
Water erosion hazard	Low

Note: Data is based on 12 sites.

Table 5.30: Summary of attributes of Alkaline yellow–brown shallow sandy duplex

Attribute	Description
Australian Soil Classification	Mesonatric or Hypernatric Brown Sodosol
Land systems	Buraminya, Charlina, Cheriton, Dundas, Halbert, Hann, Kurrawang, Newdegate
Landforms	Footslopes, playa plains, riseslopes, sandsheets
Soil texture notes	Loamy sand over light to medium clay
Soil colour	Pale brown or yellowish brown; occasionally strong brown or grey
Soil depth	Shallow to moderate (15–80 cm)
Structure and fabric	Apedal, single grain topsoil; large columnar or prismatic subsoil
Soil surface condition	Soft to firm
Topsoil pH rating (range)	Neutral (6.0–7.0)
Subsoil pH rating (range)	Strongly alkaline (8.5–9.5)
Salinity rating (EC_e)	Not saline to slightly saline (<200–400 mS/m)
Soil permeability	Very slow to slow
Available water storage	Very low to low
Wind erosion hazard	Moderate
Water erosion hazard	Low

Note: Data is based on 11 sites.

Table 5.31: Summary of attributes of Alkaline red deep sandy duplex

Attribute	Description
Australian Soil Classification	Mesonatric or Hypernatric Red Sodosol
Land systems	Carnegie, Hyden, Rowles
Landforms	Drainage floors, footslopes, loamy plains, playa plains, saline plains, sandsheets, swamps
Soil texture notes	Loamy sand over light to medium clay
Soil colour	Yellowish red to red
Soil depth	Moderate (30–80 cm)
Structure and fabric	Apedal, single grain topsoil; large columnar or prismatic subsoil
Soil surface condition	Soft to firm
Topsoil pH rating (range)	Neutral (6.0–7.0)
Subsoil pH rating (range)	Strongly alkaline (8.5–9.5)
Salinity rating (EC_e)	Not saline to slightly saline (<200–400 mS/m)
Soil permeability	Very slow to slow
Available water storage	Moderately low to low
Wind erosion hazard	Moderate
Water erosion hazard	Low

Note: Data is based on 3 sites.

Table 5.32: Summary of attributes of Alkaline yellow–brown deep sandy duplex

Attribute	Description
Australian Soil Classification	Mesonatric or Hypernatric Brown Sodosol
Land systems	Carnegie, Gransal, Lakeside
Landforms	Drainage floors, sandsheets
Soil texture notes	Fine to medium loamy sand over light to medium clay
Soil colour	Yellowish brown to brown; occasionally strong brown
Soil depth	Moderate (30–80 cm)
Structure and fabric	Apedal, single grain topsoil; large columnar or prismatic subsoil
Soil surface condition	Loose to soft
Topsoil pH rating (range)	Slightly acid to neutral (5.5–7.5)
Subsoil pH rating (range)	Strongly alkaline (8.5–9.5)
Salinity rating (EC_e)	Slightly to moderately saline (200–800 mS/m)
Soil permeability	Very slow to slow
Available water storage	Very low
Wind erosion hazard	Moderate to high
Water erosion hazard	Low to moderate

Note: Data is based on 4 sites.

Alkaline sandy duplex soil protected by dense litter on a playa plain supporting mixed eucalypt and melaleuca woodland

Soil suite 9: Loamy duplex soils with an alkaline pH in the subsoil

This suite comprises 2 soil variants: Alkaline red shallow loamy duplex is common across the survey area and it transitions to Alkaline yellow–brown (and grey) shallow loamy duplex in the south of the survey area (Table 5.33, Figure 5.8, Table 5.34).Both variants are characterised by the presence of a loamy topsoil and a distinct and rapid change in texture to a clayey subsoil that is alkaline and has carbonate minerals at depth.

This is a major suite of soils described from 53 sites across 26 land systems. Alkaline loamy duplex soils are dominant on low-lying, depositional landforms and broad plains, and are mostly vegetated by eucalypt woodland. In these landscape positions, the subsoil is usually sodic. They also occur, but less commonly, on the lower slopes and rises of land systems containing significant greenstone parent material. Where the soils form from greenstone rocks and are not strongly weathered, the subsoils are well structured and are usually not sodic. In the ASC, the sodic version classifies as a Sodosol and the non-sodic soil classifies as a Chromosol.

Water erosion can be significant on these soils and is most prevalent where tracks and fencelines concentrate natural overland flow.

Table 5.33: Summary of attributes of Alkaline red shallow loamy duplex

Attribute	Description
Australian Soil Classification	Mesonatric or Hypernatric Red Sodosol (usually Hypocalcic or Hypercalcic), Hypocalcic or Hypercalcic Red Chromosol
Land systems	Bunyip, Coolgardie, Cowalinya, Doney, Gransal, Graves, Greenmount, Gumland, Gundockerta, Johnston, Kanowna, Lefroy, Latimore, Monger, Noondoonia, Perilya, Rowles, Woolibar, Woorbla, Wyralinu, Yardilla
Landforms	Drainage floors, drainage foci, footslopes, gilgais, hillslopes, lateritic lag plains, loamy plains, riseslopes, stony plains, valley flats
Soil texture notes	Light-textured variant: sandy loam over clay loam to light clay Heavy-textured variant: clay loam over heavy clay
Soil colour	Yellowish red to red or dark red
Soil depth	Shallow to deep (15–150 cm), dependent on the structure of subsoil clay
Structure and fabric	Pedal, crumb to fine subangular blocky topsoil; subsoil varies from columnar or prismatic where sodic, to strongly structured, fine subangular blocky where not sodic
Soil surface condition	Soft to hardsetting
Topsoil pH rating (range)	Neutral to moderately alkaline (6.0–8.0)
Subsoil pH rating (range)	Strongly alkaline (8.5–9.5)
Salinity rating (EC_e)	Not saline to moderately saline (<800 mS/m)
Soil permeability	Very slow to slow
Available water storage	Low to moderate, depending on the structure of subsoil clay
Wind erosion hazard	Low
Water erosion hazard	Moderate

Note: Data is based on 41 sites.

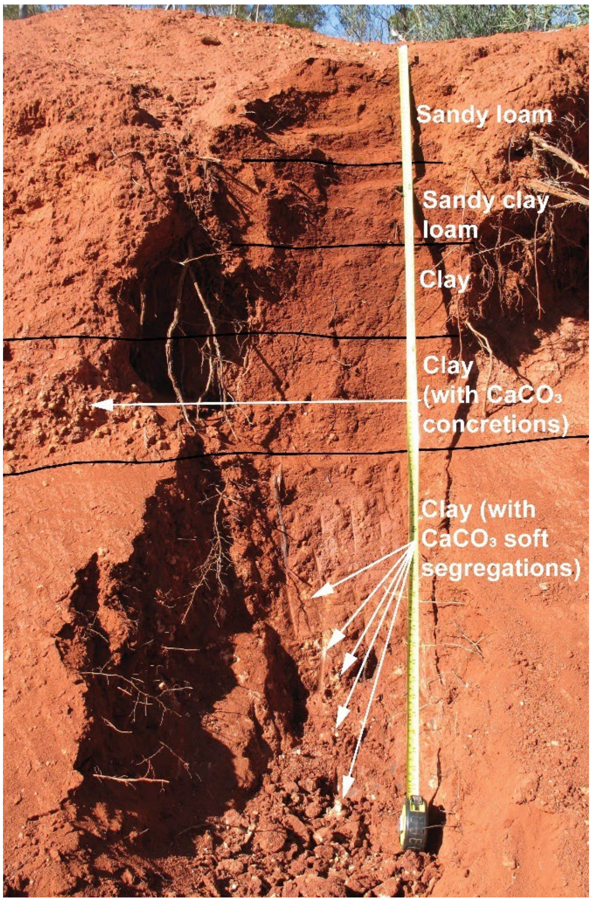


Figure 5.8: Alkaline red shallow loamy duplex soil in the Doney land system – the subsoil is atypical because the landform was a drainage depression, so the calcareous concretions were deeper in the profile than usual

Table 5.34: Summary of attributes of Alkaline yellow–brown shallow loamy duplex

Attribute	Description
Australian Soil Classification	Mesonatric or Hypernatric Brown Sodosol (usually Hypocalcic or Hypercalcic), Hypocalcic or Hypercalcic Brown Chromosol
Land systems	Coolgardie, Cronin, Frasershear, Jimberlana, Noganyer
Landforms	Drainage foci, hillslopes, loamy plains, low rises, lower footslopes, valley flats
Soil texture notes	Light-textured variant: sandy loam over clay loam to light clay Heavy-textured variant: silty clay loam over medium-heavy clay
Soil colour	Pale brown to brown or yellowish grey to grey
Soil depth	Shallow to deep (15–150 cm), depending on the structure of subsoil clay
Structure and fabric	Pedal, crumb to fine subangular blocky topsoil; subsoil varies from columnar or prismatic where sodic, to strongly structured, fine subangular blocky where not sodic
Soil surface condition	Soft to hardsetting
Topsoil pH rating (range)	Neutral to moderately alkaline (6.0–8.0)
Subsoil pH rating (range)	Strongly alkaline (8.5–9.5)
Salinity rating (EC_e)	Not saline to slightly saline (<200–400 mS/m)
Soil permeability	Very slow to slow
Available water storage	Low to moderate, depending on the structure of subsoil clay
Wind erosion hazard	Low
Water erosion hazard	Moderate

Note: Data is based on 12 sites.

Soil suite 10: Loamy duplex soils with a neutral to acid pH in the subsoil

This is a minor suite of soils described from 12 sites across 11 land systems. They mostly form on deposition zones and are vegetated by eucalypt woodland. This suite is distinguished by the presence of a loamy topsoil and an abrupt change in texture to clay subsoil that is neutral to acid and lacks carbonate minerals. Most soils described classify as Red shallow loamy duplex. Two rare variants occur: one has deeper topsoil and is classed as Red deep loamy duplex and the other occurs in the south where the red yields to Yellow–brown shallow loamy duplex. Only the Red shallow loamy duplex soil is characterised below because the variants are insignificant and very similar to that described (Table 5.35).

These soils are generally resistant to accelerated erosion.

Table 5.35: Summary of attributes of Red shallow loamy duplex

Attribute	Description
Australian Soil Classification	Red Sodosol, Red Chromosol
Land systems	Coolgardie, Cundlegum, Frasershear, Gransal, Greenmount, Gundockerta, Johnston, Kanowna, Lakeside, Lefroy, Monger, Moorebar, Woolibar
Landforms	Alluvial fans, drainage floors, footslopes, gritty-surfaced plains, loamy plains, saline alluvial plains, valley flats
Soil texture notes	Sandy clay loam over clay
Soil colour	Yellowish brown to red or dark red
Soil depth	Shallow to deep (15–150 cm), depending on the structure of subsoil clay
Structure and fabric	Pedal, crumb to fine subangular blocky topsoil; commonly columnar or prismatic sodic subsoil
Soil surface condition	Firm to hardsetting
Topsoil pH rating (range)	Slightly acid to neutral (5.5–7.5)
Subsoil pH rating (range)	Neutral (6.5–7.5); lower subsoil is occasionally moderately alkaline, but not calcareous
Salinity rating (EC_e)	Not saline to moderately saline (<200–800 mS/m)
Soil permeability	Very slow
Available water storage	Low to moderate, depending on the structure of subsoil clay
Wind erosion hazard	Low
Water erosion hazard	Moderate

Note: Data is based on 12 sites.

Soil suite 11: Clay soils

This is a common suite of soils described from 40 sites across 26 land systems. They mostly form on the lowest water-accumulating landforms of deposition zones and are vegetated by eucalypt woodland, grassland or *Duma florulenta* (lignum).

This suite has a clay texture throughout the profile, often with carbonate minerals in the subsoil. Clay mineralogy is important in distinguishing these soil types. Clay containing smectite shrinks and swells as the soil dries and wets, respectively. This imparts structural characteristics that affect water flow, permeability and rooting conditions. In contrast, clay soil dominated by kaolinite or illite does not shrink and swell as water content varies (see Soil formation section).

In the survey area, 22 of the sites examined had clay soil with significant swelling clay and 15 of these were associated with water-accumulating landforms, such as drainage foci, valley floors and fans, and gilgai depressions or gilgai plains: 15 sites were Self-mulching cracking clay and 7 were Hard cracking clay (Table 5.36, Table 5.37). Twelve sites had a small proportion of swelling clay: 11 were classed as Friable non-cracking clay and 1 as a Hard non-cracking clay (Table 5.38). Most of the non-cracking clay soils were on landforms or land systems that show signs of past or present salinity. Rare variants were shallow clay underlain by basement rock. Four sites were Shallow non-cracking clay, and 2 sites were Shallow cracking clay (Table 5.39).

Across the survey area, clay soils in water-accumulating landscapes are prone to salinity.

Table 5.36: Summary of attributes of Self-mulching cracking clay

Attribute	Description
Australian Soil Classification	Self-mulching Black or Red Vertosol
Land systems	Coolgardie, Doney, Emu, Gumland, Gnamma, Marda, Noondoonia, Rowles, Sedgeman, Woolibar, Yardilla
Landforms	Alluvial fans, drainage foci, gilgai plains, swamps
Soil texture notes	Light clay or silty clay grading to heavy clay
Soil colour	Reddish brown to red or dark red
Soil depth	Deep to very deep (>80 cm)
Structure and fabric	Pedal, polyhedral or granular topsoil; fine subangular blocky subsoil
Soil surface condition	Self-mulching
Topsoil pH rating (range)	Neutral to strongly alkaline (7.0–9.0)
Subsoil pH rating (range)	Moderately alkaline to extremely alkaline (7.5–10.0)
Salinity rating (EC_e)	Slightly saline to moderately saline (200–800 mS/m)
Soil permeability	Initially very rapid, then slow to very slow after soil wets and swells
Available water storage	High
Wind and water erosion hazard	Low

Note: Data is based on 15 sites.

Table 5.37: Summary of attributes of Hard cracking clay

Attribute	Description
Australian Soil Classification	Crusty or Epipedal or Massive Red Vertosol
Land systems	Bunyip, Johnston
Landforms	Gilgai plains, low rises, plains
Soil texture notes	Light clay grading to medium clay or heavy clay
Soil colour	Red to dark red
Soil depth	Deep to very deep (>80 cm)
Structure and fabric	Pedal, platy to angular blocky topsoil; angular blocky subsoil
Soil surface condition	Hard, often hardsetting
Topsoil pH rating (range)	Neutral to strongly alkaline (7.0–9.0)
Subsoil pH rating (range)	Moderately alkaline to extremely alkaline (7.5–10.0)
Salinity rating (EC_e)	Slightly saline to moderately saline (200–800 mS/m)
Soil permeability	Very slow
Available water storage	Moderate to high
Wind and water erosion hazard	Low

Note: Data is based on 7 sites.

Hard cracking clay soil in a drainage focus supporting *Eucalyptus salubris* (gimlet) woodland over *Eremophila ternata* in the Johnston land system

Table 5.38: Summary of attributes of Friable non-cracking clay

Attribute	Description
Australian Soil Classification	Pedaric or Hypercalcic Red Dermosol
Land systems	Coolgardie, Cowalinya, Cronin, Dunnsville, Illaara, Kanowna, Latimore, Lefroy, Moriarty
Landforms	Drainage floors, lake beds, lower footslopes, plains, rises, saline plains
Soil texture notes	Light clay grading to medium clay or heavy clay
Soil colour	Yellowish red to red
Soil depth	Deep to very deep (>80 cm)
Structure and fabric	Pedal, platy to angular blocky topsoil; angular blocky subsoil
Soil surface condition	Hard, often hardsetting
Topsoil pH rating (range)	Slightly acid to neutral (5.5–7.0)
Subsoil pH rating (range)	Neutral to strongly alkaline (7.0–9.0); occasionally acid in subsoil affected by saline watertable
Salinity rating (EC_e)	Slightly to highly saline (200–1,600 mS/m)
Soil permeability	Very slow
Available water storage	Moderate
Wind and water erosion hazard	Low

Note: Data is based on 12 sites.

Table 5.39: Summary of attributes of Shallow non-cracking clay

Attribute	Description
Australian Soil Classification	Pedaric or Hypercalcic Red Dermosol
Land systems	Coolgardie, Euchre, Gundockerta, Johnston, Widgiemooltha, Woolibar
Landforms	Drainage floors, lake beds, lower footslopes, plains, rises, saline plains
Soil texture notes	Light clay grading to medium clay or heavy clay
Soil colour	Red to dark red
Soil depth	Moderate (30–80 cm)
Structure and fabric	Pedal, platy to angular blocky topsoil; angular blocky subsoil
Soil surface condition	Hard, often hardsetting
Topsoil pH rating (range)	Slightly acid to neutral (5.5–7.0)
Subsoil pH rating (range)	Neutral to strongly alkaline (7.0–9.0)
Salinity rating (EC_e)	Slightly saline to moderately saline (200–800 mS/m)
Soil permeability	Very slow
Available water storage	Low
Wind and water erosion hazard	Low

Note: Data is based on 6 sites.

Soil suite 12: Shallow loam soils

This is a dominant and widespread suite of soils described from 133 sites. It includes a range of soils that are generally red, loamy throughout and with a root-limiting layer within 80 cm. Variations are defined according to the depth of underlying regolith. Soils underlain by competent rock are Red shallow loam and Limestone shallow loam (Table 5.40). Other shallow loams have a hardpan – which we perceive as a root-limiting layer – but have deep, permeable regolith beneath. Soils with these characteristics are Calcareous gravelly shallow loam, Calcareous shallow loam and Red–brown hardpan shallow loam (Table 5.41, Table 5.42, Table 5.43)

Red–brown hardpan shallow loam also includes Very shallow soil over hardpan; both become dominant in the north where *Acacia aneura* (mulga) woodlands are common. In contrast, Calcareous shallow loam, which also includes Very shallow soil over calcrete, dominates where eucalypt woodland occurs. Red shallow loam occupies land systems with shallow rock and outcrop.

Shallow loam soils are prone to structure degradation when trampled, which occurs in areas frequented by livestock, and this increases the potential for water erosion. They are not prone to wind erosion.

Table 5.40: Summary of attributes of Red shallow loam

Attribute	Description
Australian Soil Classification	Paralithic or Lithic Leptic Rudosol, Duric or Ferric Calcenic Tenosol, Petrocalcic Calcic Tenosol, Red Kandosol
Land systems	Bandy, Bevon, Binneringie, Charlina, Cundlegum, Dryandra, Dunnsville, Gnamma, Gransal, Graves, Gundockerta, Helag, Kanowna, Lawrence, Marmion, Moriarty, Ponton, Sedgeman, Sharpe, Symons, Woolibar, Zed; *expected in Johnston, Wallaroo*
Landforms	Drainage floors, hillslopes, loamy plains, low rises, lower footslopes, pediments*, riseslopes
Soil texture notes	Sandy loam grading to sandy clay loam or clay loam; sometimes retains uniform topsoil texture to depth
Soil colour	Reddish-brown topsoil; red to dark red subsoil
Soil depth	Moderate (30–80 cm)
Structure and fabric	Apedal, earthy throughout; occasionally with subangular blocky subsoil
Soil surface condition	Hardsetting
Topsoil pH rating (range)	Slightly acid to neutral (5.5–7.0)
Subsoil pH rating (range)	Neutral to moderately alkaline (6.5–8.0)
Salinity rating (EC_e)	Not saline to slightly saline (<200–400 mS/m)
Soil permeability	Moderately slow
Available water storage	Low to moderately low
Wind erosion hazard	Low
Water erosion hazard	Moderate

* Pediments are equivalent to ‘gritty-surfaced and stony plains’ identified in land systems first described in other rangelands inventory reports.

Note: Data is based on 27 sites.

Table 5.41: Summary of attributes of Calcareous gravelly shallow loam

Attribute	Description
Australian Soil Classification	Regolithic Lithocalcic Calcarosol, Regolithic Supracalcic Calcarosol Petrocalcic Lithocalcic Calcarosol, Petrocalcic Supracalcic Calcarosol; occasionally a Kandosol, Rudosol or Tenosol
Land systems	Charlina, Coolgardie, Cundlegum, Deadman, Doney, Dundas, Eundynie, Gransal, Gumland, Gundockerta, Illaara, Johnston, Joseph, Kanowna, Kurrawang, Monger, Sedgeman, Symons, Woolibar, Yardina
Landforms	Calcrete platforms, drainage floors, loamy plains, low rises, lower footslopes, pediments*, riseslopes
Soil texture notes	Sandy loam or silty loam, sometimes with an increase in subsoil texture to clay loam
Soil colour	Reddish-brown topsoil; yellowish-red, red or dark red subsoil
Soil depth	Moderate (30–80 cm)
Structure and fabric	Apedal, earthy
Soil surface condition	Hard, often hardsetting
Topsoil pH rating (range)	Neutral to moderately alkaline (7.0–8.5)
Subsoil pH rating (range)	Strongly alkaline (>8.5)
Salinity rating (EC_e)	Not saline to slightly saline (<200–400 mS/m); occasionally moderately saline (400–800 mS/m)
Soil permeability	Moderate
Available water storage	Very low
Wind erosion hazard	Low
Water erosion hazard	Moderate

* Pediments are equivalent to 'gritty-surfaced and stony plains' identified in land systems first described in other rangelands inventory reports.

Note: Data is based on 31 sites.

Calcareous gravelly shallow loam soil on the footslope of a low rise in the Gumland land system

Table 5.42: Summary of attributes of Calcareous shallow loam

Attribute	Description
Australian Soil Classification	Lithic Lithocalcic Calcarosol, Lithic/Paralithic/Petrocalcic Supracalcic Calcarosol, Paralithic or Lithic Calcic Calcarosol, occasionally Kandosol, Rudosol or Tenosol
Land systems	Coolgardie, Doney, Dundas, Eundynie, Frasershear, Graves, Greenmount, Gumland, Gundockerta, Hampton, Jaurdi, Kanowna, Kurrawang, Lawrence, Monger, Noganyer, Noondoonia, Symons, Woolibar, Yardina, Zanthus
Landforms	Drainage floors, hillslopes, loamy plains, low rises, lower footslopes, pediments*, plains, riseslopes
Soil texture notes	Sandy loam or clay loam, sometimes with an increase in subsoil texture to clay loam
Soil colour	Reddish-brown topsoil; yellowish-red, red or dark red subsoil
Soil depth	Moderate (30–80 cm)
Structure and fabric	Apedal, earthy
Soil surface condition	Hard, often hardsetting
Topsoil pH rating (range)	Neutral to moderately alkaline (7.0–8.5)
Subsoil pH rating (range)	Strongly alkaline (>8.5)
Salinity rating (EC_e)	Not saline to slightly saline (<200–400 mS/m); occasionally moderately saline (400–800 mS/m)
Soil permeability	Moderately slow to moderate
Available water storage	Low to moderately low
Wind erosion hazard	Low
Water erosion hazard	Moderate

* Pediments are equivalent to 'gritty-surfaced and stony plains' identified in land systems first described in other rangelands inventory reports.

Note: Data is based on 48 sites.

Calcareous shallow loam soil on the slope of a low rise in the Gundockerta land system

Table 5.43: Summary of attributes of Red–brown hardpan shallow loam

Attribute	Description
Australian Soil Classification	Duric Red Kandosol, Duric Leptic Tenosol
Land systems	Deadman, Doney, Euchre, Gundockerta, Helag, Kirgella, Kwelkan, Manning, Moriarty, Pindar, Tealtoo, Yowie
Landforms	Drainage floors, hillslopes, lower footslopes, loamy plains, low rises, pediments*, riseslopes
Soil texture notes	Sandy clay loam or silty clay loam, sometimes with an increase in subsoil texture to clay loam
Soil colour	Red to dark red
Soil depth	Moderate (30–80 cm)
Structure and fabric	Apedal, earthy
Soil surface condition	Hardsetting
Topsoil pH rating (range)	Strongly acid to slightly acid (4.5–6.0)
Subsoil pH rating (range)	Neutral to moderately alkaline (6.0–8.0)
Salinity rating (EC_e)	Not saline (<200 mS/m)
Soil permeability	Moderately slow to moderate
Available water storage	Low to moderately low
Wind erosion hazard	Low
Water erosion hazard	Low

* Pediments are equivalent to 'gritty-surfaced and stony plains' identified in land systems first described in other rangelands inventory reports.

Note: Data is based on 27 sites.

Red–brown hardpan shallow loam soil supporting *Acacia aneura* (mulga) woodland in the Yowie land system

Soil suite 13: Shallow sand soils

This is a minor suite of soils described from 9 sites. It is usually underlain by rock and mostly fringes granitic rock outcrop. These soils are skeletal with a gritty, coarse sandy topsoil that usually continues to the rock basement, but occasionally transitions to loamy subsoil above rock. They mostly classify as Red shallow sand and are most common in the Bandy, Marmion and Sedgeman land systems (Table 5.44). Occasionally the soil colour is yellow or brown, but otherwise is similar.

An uncommon variant unrelated to the skeletal soils described above is a red or yellowish-brown soil consisting of fine sand underlain by ferricrete hardpan.

Shallow sand soils are prone to water erosion, particularly where they are subjected to overland flow emanating from surrounding rocky land systems.

Table 5.44: Summary of attributes of Red shallow sand

Attribute	Description
Australian Soil Classification	Lithic Leptic Rudosol, Lithic Red-Orthic Tenosol
Land systems	Bandy, Graves, Joseph, Kirgella, Marmion, Noganyer, Sedgeman, Yandamurrina; *expected in Johnston, Kartukartunga, Wallaroo*
Landforms	Hillslopes, low rises, pediments*
Soil texture notes	Medium or coarse loamy sand grading to coarse clayey sand
Soil colour	Reddish-brown topsoil; red to dark red subsoil
Soil depth	Moderate (30–80 cm)
Structure and fabric	Apedal, earthy, occasionally with subangular blocky subsoil
Soil surface condition	Hard, often hardsetting
Topsoil and subsoil pH rating (range)	Moderately acid to neutral (5.0–7.0)
Salinity rating (EC_e)	Not saline (<200 mS/m)
Soil permeability	Moderate overall (because of the impermeable rock); very rapid in topsoil
Available water storage	Low to moderately low
Wind erosion hazard	Low
Water erosion hazard	Low to moderate, only erodes after soil is saturated

* Pediments are equivalent to ‘gritty-surfaced and stony plains’ identified in land systems first described in other rangelands inventory reports.

Note: Data is based on 9 sites.

Soil suite 14: Shallow stony soils with a neutral to acid pH in the subsoil

This suite of soils is widespread and fringes rock outcrop on hills and ranges. It is more variable than Shallow sand (soil suite 13) and is shallower or has a higher proportion of coarse fragments. Fifty-one sites were described, and soil types include Very shallow soil and Stony soil (Table 5.45, Table 5.46). Both are skeletal soils that have a high proportion of stones and lithic gravel throughout the profile. Very shallow soil is underlain by rock within 30 cm of the surface and may contain gravels and stones. In contrast, Stony soil has many gravels and stones and may be deep. They have no calcium carbonate, and the soil texture is variable, reflecting the variety of rocks these form on. These soils commonly form on granite, gneiss, metasedimentary rocks including banded iron formation, but sometimes are found on basalt and other mafic rocks.

Table 5.45: Summary of attributes of Very shallow soil

Attribute	Description
Australian Soil Classification	Lithic Leptic Rudosol
Land systems	Bandy, Bungalbin, Coolgardie, Dryandra, Gransal, Gundockerta, Hampton, Jaurdi, Kurrawang, Lawrence, Moriarty, Sedgeman, Wyralinu, Yandamurrina; *expected in Greenmount, Johnston, Kanowna, Kartukartunga, Symons, Wallaroo*
Landforms	Domes, hillcrests, hillslopes, low rises, ridges, riseslopes
Soil texture and coarse fragments notes	Variable, mostly sandy loam to sandy clay loam, occasionally sand or clay; many gravels and stones
Soil colour	Red or brown, occasionally yellowish brown
Soil depth	Very shallow to shallow (<30 cm)
Structure and fabric	Apedal, earthy or apedal, single grain
Soil surface condition	Loose
Topsoil and subsoil pH rating (range)	Slightly acid to neutral (5.5–7.5)
Salinity rating (EC_e)	Not saline (<200 mS/m)
Soil permeability	Slow (because of the impermeable bedrock near the surface)
Available water storage	Very low
Wind and water erosion hazard	Low

Note: Data is based on 36 sites.

Table 5.46: Summary of attributes of Stony soil

Attribute	Description
Australian Soil Classification	Lithic Leptic Rudosol
Land systems	Binneringie, Bungalbin, Coolgardie, Dryandra, Graves, Hampton, Jaurdi, Jimberlana, Lawrence, Quartzitehill, Wallaroo, Zed; *expected in Greenmount, Johnston, Kanowna, Kartukartunga, Symons*
Landforms	Domes, footslopes, hillcrests, hillslopes, low rises, riseslopes
Soil texture and coarse fragments notes	Sand, occasionally loam; many gravels and stones
Soil colour	Variable
Soil depth	Moderate to deep (30–150 cm)
Structure and fabric	Apedal, earthy or apedal, single grain
Soil surface condition	Loose
Topsoil and subsoil pH rating (range)	Slightly acid to neutral (5.5–7.5)
Salinity rating (EC_e)	Not saline (<200 mS/m)
Soil permeability	Moderate (because of the impermeable bedrock at depth)
Available water storage	Very low
Wind and water erosion hazard	Low

Note: Data is based on 15 sites.

Soil suite 15: Calcareous shallow stony soils

This suite of soils is found on hills and ranges of ultramafic and mafic rocks of Archean and Proterozoic provenance. The south and central parts of the survey area have more skeletal soils with carbonates, likely influenced by carbonates deposited during past marine transgressions and subsequent eolian accessions. Calcareous stony soils also form on spongolite rock. In this situation, the calcareous rinds common to calcium carbonate concretions envelope spongolite stones and boulders (Figure 5.1).

The suite was described from 48 sites and includes Calcareous very shallow soil and Calcareous stony soil (Table 5.47, Table 5.48). Both are skeletal soils containing a high proportion of stones and lithic gravel. The soil texture is usually a sandy loam to silty loam that is calcareous throughout. Carbonate minerals often coat the stones and lithic fragments.

These soils are prone to water erosion, particularly where surrounding landforms contribute to overland flow and where tracks and fencelines concentrate flow.

Table 5.47: Summary of attributes of Calcareous very shallow soil

Attribute	Description
Australian Soil Classification	Lithic Leptic Rudosol, Supracalcic or Lithocalcic Calcarosol
Land systems	Coolgardie, Graves, Gundockerta, Hampton, Jaurdi, Kurrawang, Lawrence, Moriarty, Noganyer, Sedgeman, Woolibar
Landforms	Footslopes, hillcrests, hillslopes, low rises, ridges, riseslopes
Soil texture and coarse fragments notes	Sandy loam to silty loam; many gravels and stones
Soil colour	Reddish brown to dark red or grey to pale red
Soil depth	Very shallow to shallow (<30 cm)
Structure and fabric	Apedal, earthy
Soil surface condition	Soft to firm, stony surface
Topsoil and subsoil pH rating (range)	Strongly alkaline (>8.5)
Salinity rating (EC_e)	Not saline (<200 mS/m); occasionally slightly saline (200–400 mS/m)
Soil permeability	Slow
Available water storage	Very low
Wind and water erosion hazard	Low

Note: Data is based on 34 sites.

Table 5.48: Summary of attributes of Calcareous stony soil

Attribute	Description
Australian Soil Classification	Lithic Lithocalcic Calcarosol, Paralithic Lithocalcic Calcarosol, Calcic Calcarosol, Lithic Leptic Rudosol, Lithic Lithocalcic Tenosol
Land systems	Coolgardie, Eundynie, Illaara, Jimberlana, Kanowna, Lawrence, Latimore, Moriarty, Quartzitehill, Woolibar, Yandamurrina
Landforms	Hillcrests, hillslopes, low rises, ridges, riseslopes
Soil texture and coarse fragments notes	Sandy loam; many gravels and stones
Soil colour	Yellowish red to reddish brown
Soil depth	Moderate to deep (30–150 cm)
Structure and fabric	Apedal, earthy
Soil surface condition	Soft to firm, stony surface
Topsoil and subsoil pH rating (range)	Strongly alkaline (>8.5)
Salinity rating (EC_e)	Not saline (<200 mS/m)
Soil permeability	Moderately slow
Available water storage	Low
Wind and water erosion hazard	Low

Note: Data is based on 14 sites.

Soil suite 16: Bare rock

Bare rock classifies as a WA Soil Group and, although it is not soil, it is identified as a land surface (Table 5.49). The largest and most abundant outcrops occur on rocks most resistant to weathering. This is mostly granite, gneiss, basalt and metasedimentary rocks including banded iron formation. Outcrops of other rock are less common and less extensive but occur in many land systems. We list land systems where outcrops are common and expected, rather than listing land systems where we encountered Bare rock. We did this because we undersampled Bare rock sites that have very low grazing value and no vegetation or soil to describe.

Table 5.49: Summary of attributes of Bare rock

Attribute	Description
Australian Soil Classification	Lithic Leptic Rudosol
Land systems	Balladonia, Bandy, Bevon, Binneringie, Bungalbin, Coolgardie, Dryandra, Gnamma, Gransal, Graves, Greenmount, Gundockerta, Hampton, Jaurdi, Jimberlana, Kanowna, Kartukartunga, Kurrawang, Kwelkan, Latimore, Lawrence, Moriarty, Noganyer, Norie, Quartzitehill, Sedgeman, Symons, Wallaroo, Widgiemooltha, Wyralinu, Yandamurrina, Zed
Landforms	Domes, hillcrests, hillslopes, low rises, ridges, riseslopes
Soil texture notes	Thin veneer of stones, gravels, sand and possibly loam
Soil colour	Variable
Soil depth	Very shallow (<15 cm)
Structure and fabric	Apedal, single grain
Soil surface condition	Loose
Salinity rating (EC_e)	Not saline (<200 mS/m)
Available water storage	Very low
Wind and water erosion hazard	None

Note: Data is based on 8 sites.

Soil suite 17: Ironstone gravelly soils

This suite is widespread and contains a diverse range of soils that have ironstone gravels at shallow depth. They can be grouped into 5 main categories whose distribution results from differing parent material, geomorphological history and vegetation distribution. Ironstone gravelly soils have a protracted history, having formed in past times and forming contemporaneously in different parts of the survey area (see Soil formation section for our conceptual model describing the formation of iron concretions in soil). They show high resistance to erosion, so that the presumed older soils persist across a significant portion of the survey area and support a variety of vegetation communities.

We regard the Shallow sandy gravel and Deep sandy gravel as likely contemporaneous because they retain an intact sandy horizon over the gravel layer and are currently populated by diverse heath species (Table 5.50). These soils generally have a brown or yellow to yellowish-red topsoil and are prevalent on sandplain underlain by granite and gneiss of the central and western land systems of Joseph and Bannar. Variants are common in the Newdegate and Hyden land systems. Only 6 such sites were classified because we only conducted reconnaissance survey over the extensive sandplain that is not used for rangeland production.

Very shallow soil over ferricrete hardpan is included with this suite because it has similar genesis (Table 5.51). This soil is uncommon but is locally abundant on the crests and upper slopes of land systems where iron-rich parent material or breakaways are common, such as in the Bevon, Bungalbin, Cundlegum, Dryandra, Euchre, Greenmount, Helena, Hyden, Illaara, Ironcap, Kurrawang and Latimore land systems.

Loamy variants of ironstone gravelly soils that are not calcareous are predominantly Loamy gravel and Shallow loamy gravel, which are similar except for depth (Table 5.52, Table 5.53, Figure 5.9). Contemporary loamy gravel and shallow loamy gravel soils form on mafic, iron-rich parent material in a similar way to how ironstone gravels form in sandplain (see Soil formation section). Shallow loamy gravel soils occupy the crests and upper backslopes of breakaways and Loamy gravel soils occupy low rises and the breakaway lower backslopes and footslopes of the Bannar, Greenmount, Helena, Illaara, Jackson, Latimore and Monger land systems.

Loamy gravel soils also form in colluvial situations when ironstone gravels and ferricrete on crests and breakaways weather to fine ironstone gravels in a loamy matrix and erode to deposit in lower slope positions. The Loamy gravel soils of the Illaara and Monger land systems are the weathered and eroded remnants of breakaways and ironstone gravelly land surfaces, such as those present in the Latimore land system. These soils predominantly form in the zone of eastward flowing rivers and appear to be an older generation of soils containing iron concretions, which are retained in the landscape because of their resistance to erosion and their location in the lower parts of the drainage network, which have low gradients and low erosive potential.

The Calcareous loamy ironstone gravel and Shallow calcrete ironstone gravel are a unique subset that form when previously neutral to acid ironstone gravelly soil becomes calcareous when vegetation hydraulically redistributes carbonate-rich water into the rooting zone (Table 5.54, Figure 5.10). *Eucalyptus lesouefii* (Goldfields blackbutt) and *Casuarina pauper* (black oak) are frequently located on this soil.

Table 5.50: Summary of attributes of Shallow sandy gravel and Deep sandy gravel

Attribute	Description
Australian Soil Classification	Petroferric Sesqui-nodular Tenosol
Land systems	Bannar, Greenmount, Illaara, Joseph
Landforms	Lateritic sandplains, low rises, riseslopes
Soil texture and coarse fragments notes	Fine sand to clayey sand; many iron concretions
Soil colour	Yellowish brown or strong brown to yellowish red
Soil depth	Moderate to very deep (>80 cm)
Structure and fabric	Apedal, earthy
Soil surface condition	Loose or soft
Topsoil and subsoil pH rating (range)	Moderately acid to neutral (5.0–6.5)
Salinity rating (EC_e)	Not saline (<200 mS/m)
Soil permeability	Rapid
Available water storage	Moderate
Wind and water erosion hazard	Low

Note: Data is based on 4 sites.

Table 5.51: Summary of attributes of Very shallow soil over ferricrete hardpan

Attribute	Description
Australian Soil Classification	Petroferric Sesqui-nodular Tenosol, Paralithic Sesqui-nodular Tenosol Ferric Clastic Rudosol
Land systems	Bevon, Cundlegum, Dryandra, Euchre, Eundynie, Graves, Greenmount, Helag, Helena, Hyden, Illaara, Ironcap, Latimore, Monger, Newdegate
Landforms	Breakaways, hillcrests, hillslopes, lateritic sandplains, low rises, riseslopes
Soil texture and coarse fragments notes	Fine loamy sand to fine sandy loam; many iron concretions
Soil colour	Strong brown to red
Soil depth	Very shallow to shallow (<30 cm)
Structure and fabric	Apedal, single grain to earthy
Soil surface condition	Loose or soft
Topsoil and subsoil pH rating (range)	Slightly acid (5.5–6.0)
Salinity rating (EC_e)	Not saline (<200 mS/m)
Soil permeability	Slow to moderately slow (rapid into topsoil but limited by shallow hardpan)
Available water storage	Very low
Wind and water erosion hazard	Low

Note: Data is based on 17 sites.

Table 5.52: Summary of attributes of Loamy gravel

Attribute	Description
Australian Soil Classification	Petroferric Sesqui-nodular Tenosol, Paralithic Sesqui-nodular Tenosol Petroferric Brown Kandosol
Land systems	Bannar, Greenmount, Gumland, Hyden, Jackson
Landforms	Footslopes, hillcrests, hillslopes, lateritic sandplains, low rises, riseslopes
Soil texture and coarse fragments notes	Fine sandy loam grading to fine sandy clay loam; many iron concretions
Soil colour	Strong brown to red
Soil depth	Deep (80–150 cm)
Structure and fabric	Apedal, earthy
Soil surface condition	Soft
Topsoil and subsoil pH rating (range)	Moderately acid to neutral (5.0–6.5)
Salinity rating (EC_e)	Not saline (<200 mS/m)
Soil permeability	Moderately rapid to moderate
Available water storage	Moderate
Wind and water erosion hazard	Low

Note: Data is based on 7 sites.

Table 5.53: Summary of attributes of Shallow loamy gravel

Attribute	Description
Australian Soil Classification	Petroferric Sesqui-nodular Tenosol
Land systems	Bannar, Helena, Illaara, Johnston, Kurrawang, Latimore, Monger, Newdegate
Landforms	Footslopes, lateritic sandplains, loamy plains, low rises, riseslopes
Soil texture and coarse fragments notes	Fine sandy loam throughout or grading to clay loam at depth; many iron concretions
Soil colour	Yellowish red to brown or red
Soil depth	Moderate (30–80 cm)
Structure and fabric	Apedal, earthy
Soil surface condition	Soft
Topsoil and subsoil pH rating (range)	Slightly acid to neutral (5.5–6.5)
Salinity rating (EC_e)	Not saline (<200 mS/m)
Soil permeability	Low to moderate
Available water storage	Low
Wind and water erosion hazard	Low

Note: Data is based on 13 sites.

Figure 5.9: Shallow loamy gravel soil in the Greenmount land system – the subsoil is indurated by secondary cementation caused by microbial precipitation of iron; the round feature immediately right and halfway up the handle is an old root channel infilled by iron (Fe) concretions from the topsoil

Table 5.54: Summary of attributes of Calcareous loamy ironstone gravel and Shallow calcrete ironstone gravel

Attribute	Description
Australian Soil Classification	Ferric Calcenic Tenosol, Petrocalcic or Reticulate Sesqui-nodular Tenosol
Land systems	Bungalbin, Gumland, Gnamma, Hampton, Helag, Illaara, Johnston, Moriarty
Landforms	Footslopes, hillcrests, hillslopes, lateritic lag plains, loamy plains, low rises, riseslopes
Soil texture and coarse fragments notes	Fine sandy loam throughout or grading to clay loam at depth; many to abundant iron concretions
Soil colour	Reddish brown to red or dark red
Soil depth	Moderate to deep (30–150 cm)
Structure and fabric	Apedal, earthy
Soil surface condition	Soft
Topsoil pH rating (range)	Neutral to moderately alkaline (6.5–8.5)
Subsoil pH rating (range)	Strongly alkaline (8.5–9.5)
Salinity rating (EC_e)	Not saline to highly saline (<200–1,600 mS/m)
Soil permeability	Moderately slow to moderate
Available water storage	Very low to low
Wind and water erosion hazard	Low

Note: Data is based on 14 sites.

Figure 5.10: Calcareous loamy ironstone gravelly soil in the Moriarty land system – the subsoil (from about 30 cm to the base of the pit) has pale calcareous precipitation that 'overprints' the iron concretions; this was a common soil beneath *Casuarina pauper* (black oak)

Soil formation

This conceptual model of soil and landscape evolution aims to explain the variety and distribution of soil across the survey area, as recommended by McKenzie and Grundy (2008) to maximise the benefit of land surveys over mere inventories. This discussion documents the key findings of the survey related to soil formation. For a more complete context, refer also to the Landscape evolution and Climate chapters.

Principal biological processes contributing to soil formation

The southern Goldfields survey area provides a unique vista from which to identify underlying processes that most contribute to soil and landscape evolution. The area:

- is formed from some of the oldest rocks on Earth, and thus encourages a 'deep-time' view of Earth's biological evolution from the first bacteria to present diversity
- retains the history of the interrelated mineral and biotic evolution of Earth
- is tectonically stable and subjected only to minor regional and local earth movements caused by lithospheric rafting over the mantle as it has moved north during the Cenozoic
- has parent materials that cover the suite of ultramafic to siliceous igneous, and sandy to calcareous clayey sediments
- has surfaces that range in age from young (unweathered rock) to relatively ancient and deeply weathered
- has experienced past climate regimes that transitioned from cool temperate to warm temperate and has since become increasingly arid, so that now the area is semi-arid Mediterranean to arid desert
- has remained geographically isolated over the Cenozoic so retains a straightforward evolutionary history
- contains a great diversity of plant life
- has a large range of rhizosphere symbiotic associations.

We recognise that all soil forming factors popularised by Jenny (1941) contribute to soil development in the survey area. However, we restrict our discussion to biological aspects because we identify features, in soil and soil surfaces, which are significantly influenced by biochemical processes. In this respect we concur with Lintern et al. (2013, p 6) who state that '…disparity between biotic and abiotic processes at the Earth's surface is, at best, indistinct'.

Soils of the survey area are variably concentrated in iron minerals, calcium carbonate minerals and clay minerals, in distinct layers and distributed throughout, and some land surfaces are strewn with concretions enriched in iron and manganese. Our conceptual model relates these characteristics to the crucial role ecosystems play in constructing soils, which optimises niches for extant species to control the supply of sparse water and nutrients. Within ecosystems of the survey area, plants and their rhizosphere symbiotic associates of fungi, bacteria and archaea bioengineer soils and contribute to positive feedback mechanisms that further benefit extant ecologies, as described, for example, by Verboom and Pate (2006a, 2013), Lambers et al. (2009), Phillips (2009), van Nuland et al. (2016), Jacoby et al. (2017) and Davies et al. (2020). These feedback mechanisms result from the evolutionary history of the soils and ecosystems in which they occur. South-western Australia is a biodiversity hotspot (Hopper et al. 2021) with a diverse array of rhizosphere symbioses (Brundrett and Tedersoo 2018), and both expanded during dynamic geological and paleoclimatic periods important for the survey area. The resulting soil diversity reflects this biodiversity and contributes to its expansion. In turn, the ecosystems continue to evolve and increase in complexity, such that the soil–ecosystem continuum can be considered both emergent and self-organising (see Addiscott 2010a, 2010b, 2011 for detailed discussion).

Below, we provide a summary of principle processes and describe the dominant features of soils and related ecosystems of the survey area.

Microorganisms are instrumental in the mineralogical evolution of Earth (Hazen 2008, 2010), making it habitable for higher forms of life (Konhauser 2007). Terrestrial microorganisms, mostly fed from by-products of plant photosynthesis, drive biogeochemical cycles in soil by facilitating redox processes within soil-water films, mediating mineral precipitation and dissolution, and sorbing and concentrating metal cations and anions (Konhauser 2007). Bacteria are ubiquitous in precipitating minerals containing elements essential for life (see review by Douglas and Beveridge 1998) and can generate minerals of silicate clay, iron, calcium carbonate, manganese, phosphorus, sulfur and others (Douglas and Beveridge 1998; Konhauser and Urrutia 1999; Konhauser 1998, Konhauser et al. 2017; Lingappa et al. 2021; Picard et al. 2016; Seifan and Berenjian 2019; Tazaki 1997, 2006; Wagai et al. 2020). Bacteria, archaea and cyanobacteria have multiple mechanisms to bind, manipulate and immobilise metals (Konhauser 2007). Bacteria and archaea have a uniquely high iron requirement, using it as a biocatalyst, electron carrier, oxidiser and for energy (Andrews et al. 2003). Cyanobacteria have a high iron and manganese requirement, in part because they are critical elements in enzymes that catalyse chemical processes during photosynthesis (Sharon et al. 2014; Eisenhut 2020).

Bacteria, archaea and cyanobacteria have evolved strategies to improve survival. They exude extracellular polymeric substances (EPS) to prevent desiccation, facilitate communication, promote communal living and solubilise minerals to enhance nutrient supply (Konhauser 2007; Finlay et al. 2020). Fungi also exude EPS and organic acids that chelate metals and increase solubility, thereby mediating formation of metallic minerals including oxides, phosphates, carbonates and oxalates (Liang and Gadd 2017). Extracellular polymeric substances also influence soil structure and store metals proximal to microbes for subsequent use in metabolic processes and to prevent toxicities (Costa et al. 2018; Pal and Paul 2008).

Terrestrial soil is the most biologically active compartment of the biosphere and hosts exceptional microbial diversity, resulting from the multitude of niches available within the three-dimensional soil environment (Wang and Or 2013; Tecon and Or 2017). Soil varies in physical, chemical and soil water characteristics over space and time and these characteristics are modified by biological activity. Sandy and loamy soils of the survey area commonly have concretions formed by enrichment of iron oxide or calcium carbonate. Soils consisting of clay throughout the profile or containing clay subsoil have structural units called peds. Concretions and peds both have predominantly small pores and are preferred microbial habitat (PMH) because they retain sufficient moisture to support microbes even when surrounding soil is dry, provide physical refuge from predators, and act as microbial evolutionary incubators (Hassink et al. 1993; Rillig et al. 2017). Cemented concretions are long-lasting in the soil and on the surface, where they significantly armour the land, protecting it from erosion and influencing its geomorphologic evolution. Inventory site 284 in the Coolgardie land system exemplifies short-range lateral and vertical soil profile variability that produces diverse microbial habitats (Figure 5.11). The soils have heterogeneous soil capillarity that, under episodic rainfall, retains variable moisture regimes within soil profiles and over time.

The soil components that act as PMH influence the cycling and nutrition of phosphorus for plants and their rhizosphere symbionts. Phosphorus is essential for all life and is the limiting nutrient for most ecosystems of the survey area (Lambers et al. 2006; Hopper et al. 2021) because it is highly immobile in soil in both organic and inorganic forms. Plants can only access phosphorus as inorganic orthophosphate from the soil solution. However, orthophosphate rapidly precipitates out of the soil solution because it binds strongly to iron minerals, aluminium minerals and calcium minerals (Penn and Camberato 2019). These minerals are present in abundance in different soils of the survey area, so orthophosphate is generally scarce.

Figure 5.11: A graphic example of short-range lateral and vertical soil profile variability highlighting variable matric potential zones that act as niches for soil microbial diversity. These photographs were taken in a trench about 80 m long down a single hillslope.
A) Calcareous hardpan shallow loam with deeply weathered regolith retaining rock fabric and vegetated by *Eucalyptus lesouefii* (Goldfields blackbutt)
B) Friable non-cracking clay with calcareous subsoil and vegetated by saltbush
C) Shallow stony soil (not calcareous) in a small pocket surrounded by bare rock that shows calcium carbonate coatings developing
D) Calcareous shallow loam with developing calcareous concretions and underlain by weathering rock

Organic sources of phosphorus comprise more than half of all phosphorus in most soil (Richardson 2001), but plants cannot directly access it. Phosphorus bound to organic matter must first be converted to orthophosphate by acid or alkaline phosphatase enzymes suited to the pH environment of the soil. These enzymes are produced by archaea, bacteria, fungi and plants.

Inorganic phosphorus bound to soil minerals is mostly dissociated via biochemical processes (Lambers et al. 2006; Richardson 2001). Plants, fungi and bacteria exude protons, organic acids and siderophores to release mineral-bound orthophosphate from metallic minerals in soil.

These organic compounds chelate metallic cations including iron and calcium, binding to the metals and mobilising them in soil solution. Microbes living in the PMH of soil consume the organic component, precipitating the metallic part directly or via microbial biochemical processes. Over time, the progressive concentration of iron and calcium ions forms indurated pans and concretions with concentric rinds. Iron oxide and calcium carbonate concretions of the survey area both form this way and display these rinds.

The functioning ecosystem maintains an adequate concentration of orthophosphate in soil solution by using biochemical processes to release inorganic orthophosphate from soil minerals and to convert organic phosphorus to orthophosphate. Most plants rely on rhizosphere symbioses to maintain adequate phosphorus status.

Brundrett and Tedersoo (2018) reviewed current knowledge of evolutionary history of plant–fungi symbioses, known as mycorrhizae. These authors highlighted the role of climate change and increasing complexity of habitat and soil during the second wave (Cretaceous) and third wave (Paleogene) of mycorrhizal evolution. These waves diversified mycorrhizal types from ancestral arbuscular mycorrhiza to ectomycorrhizal and non-mycorrhizal rooting morphologies common to higher plants. These authors identify that this increasing diversity and complexity of symbiotic relationships provides a competitive advantage to ectomycorrhizal and non-mycorrhizal plants, enabling temperate regions to be colonised by angiosperm woodlands (see also the Climate chapter and Martin et al. 2016). Mycorrhizal associations increase uptake of water, phosphorus, nitrogen and micronutrients. They also protect against metal toxicity, provide a competitive advantage, defend against herbivory and improve soil structure (Albornoz et al. 2021).

Woody perennial plants with deep roots and their mycorrhizae extract groundwater and minerals from the deep regolith of the survey area (Lintern et al. 2013). The minerals are redistributed to surficial and subsurface soils via plant biomass. Some water – presumably containing dissolved mineral ions – is redistributed to high capillarity PMH zones of subsoil via the root network of plants. This occurs during nights when the vapour pressure deficit is higher in subsoil than in air (Brooksbank et al. 2011). This redistribution of water and minerals from the deep regolith to the subsoil enhances rhizosphere habitat, benefiting microbial symbionts and plants with shallower roots. Mycorrhizal mining for phosphorus and other minerals from deep regolith and fresh parent material is important for maintaining ecosystem stability and has consequences for geomorphological processes (Finlay et al. 2020; Stuart et al. 2022).

Formation of calcium carbonate concretions and pans

Calcium is critical for intercellular signalling and for initiating mycorrhizal associations, despite also inducing intracellular toxicity at even low concentrations (Crichton 2012; Navazio and Mariani 2008). Plants from the Casuarinaceae, Fabaceae and Myrtaceae families dominate alkaline and calcareous soils common to the diverse woodlands of the survey area. Plants from these families and their ectomycorrhizal fungi associates form oxalate, an organic anion, to manipulate calcium ions internally and within the soil environment by producing calcium oxalate, which permits the plant to regulate intercellular calcium ion activity, calcium toxicity and reduce herbivory. Calcium regulation by plants is especially important on soils that contain abundant calcium carbonate: calcium entry to roots is controlled by substrate concentrations rather than metabolic requirements, and high intracellular calcium concentrations are toxic (Franceschi and Nakata 2005). Further, ectomycorrhizal fungi induce accumulation of calcium oxalate in associated *Eucalyptus* species (Pylro et al. 2013). A tripartite symbiosis between oxalate-producing plants, rhizosphere fungi and oxalotrophic bacteria can convert calcium oxalate from plants and fungi into soil calcium carbonate (Syed et al. 2020). This mechanism is likely present in carbonate-rich soils in the survey area. The Casuarinaceae family is known to have specialist oxalate-secreting tissues (Berg 1994), and calcium oxalate is associated with free-living, symbiotic and pathogenic fungi (Gadd 1999), which all associate with eucalypt communities. We identified soil calcium carbonate nodules and pans with vegetation including *Eucalyptus lesouefii* (Goldfields blackbutt), *E. oleosa* (giant mallee) and *Casuarina pauper* (black oak).

Eucalyptus lesouefii and *Casuarina pauper* are widespread species that overprint previously non-calcareous soils with copious finely divided calcium carbonate, calcium carbonate concretions or dense calcium carbonate pans. The calcium carbonate features of these soils commonly have abundant iron concretions embedded, which we suppose indicate an earlier ironstone gravel soil type, akin to the soil features described by Verboom and Pate (2006b).

Most of the calcium carbonate derives from marine sediments deposited to the south of paleo-shorelines in the south and east of the survey area (see Landscape evolution and Climate chapters). Some of this source material is redistributed further inland by wind (Dart et al. 2007) and organic cycling via hydraulic redistribution, litterfall and windblown ash. Some calcium is also extracted by mycorrhizal 'mining' from primary minerals in crystalline rock and converted to calcium carbonate by biochemical weathering. This process is a more important source of calcium in the north than in the south because in the north, marine sources of calcium carbonate are lesser and the calcium content of primary minerals in underlying crystalline rocks is generally greater than in the south.

The role of vegetation and associated mycorrhizae in concentrating calcium carbonate within surficial soils perhaps partly explains soil idiosyncrasies and the geomorphic distribution that contravenes climate-related mechanisms for carbonate accumulations. Despite calcium carbonate being considered a soil feature reflecting aridity, accumulations of calcium carbonate in soil are greatest in the south of the survey area where the climate is less arid and the crystalline basement is generally less endowed with calcium-rich primary minerals, compared to the arid greenstone terrain to the north (see Grevenitz 2006 for a detailed discussion).

Many soils of the survey area retain an intact topsoil and contain calcium carbonate concretions mostly in lower soil layers of PMH. The Dundas, Gumbelt, Lakeside, Noondoonia and Zanthus land systems are dominated by eucalypt woodland and are underlain by regolith likely to yield significant calcium-laden groundwater. These land systems exemplify landscapes composed of extensive soils containing biogenic calcium carbonates. By contrast, several land systems have surficial calcium concretions or hardpans and eroded margins. Small calcrete platforms, with crescent planform reminiscent of lunette dunes, are found in the Carnegie, Cheriton, Cronin, Deadman, Forrestania, Lakeside and Rowles land systems. The calcrete platforms are relict dunes forming calcrete ridges that are resistant to erosion because they have coarse concretions or hardpans protecting the surface. Nevertheless, these platforms continue to develop new soil and support diverse ecologies.

The Yandamurrina land system has a foundation of geometrically jointed, Proterozoic crystalline rock composed of calcium-rich primary minerals. The 'calcrete rises' landform, which consists of calcareous soil with calcium carbonate concretions and hardpans, aligns with the underlying jointing patterns and stands several metres above the surrounding plains. By contrast, the surrounding plains form on unjointed rock and contain the 'pediment and pediplain' landform, which consists of shallow soils that are not calcareous or have only minor calcium carbonate concretions. We postulate that the joints contain additional groundwater that deep-rooted trees and their associated ectomycorrhizal fungi can access, in addition to supplying nutrients weathered from rock (Schmalenberger et al. 2015). We envision hydraulic redistribution to soils overlying joints and subsequent conversion of biogenic calcium oxalate to calcium carbonate on surfaces of concretions and hardpans. By contrast, this process is absent or much reduced in intensity on pediments and pediplains because groundwater is scarce where jointing is absent. The calcium carbonate platforms are resistant to erosion because the gravel-sized concretions and extensive hardpans armour the surface from raindrop impact, whereas the ‘pediment and pediplain’ landform have shallow soils are more easily eroded because they lack calcium carbonate concretions and hardpans. Over time, erosive episodes cause the calcrete rises landform to become elevated in comparison to the low-lying pediment and pediplain’ landform.

Formation of iron concretions and rhizosphere sheaths

Proteaceae are dominant plants in sandplain and on ironstone gravel soils of the survey area. Rhizosphere associations of these plants have evolved from ancestral mycorrhizal symbioses, and they now do not form mycorrhizae (Brundrett and Tedersoo 2018). Instead, when signalled by the concentration of key nutrients and by chemical stimuli from soil bacteria that inhabit iron-rich rhizosphere sheaths and iron concretions, plants of the Proteaceae family – and some other species including *Allocasuarina* – grow specialised cluster roots that exude copious organic acids into their rhizosphere to access scarce phosphorus (Pate et al. 2001; Lamont 2003; Verboom and Pate 2003; Shane and Lambers 2005). The exudates are carboxylates including citrate, malate and oxalate, and they bind metal cations, such as iron, aluminium and calcium, to access phosphorus, manganese and zinc from insoluble organic and inorganic forms (Lamont 2003; Shane and Lambers 2005). The chemical binding of carboxylates to metallic cations releases sparse phosphate from soil exchange sites for uptake by the plant roots. Phosphorus uptake by plants is enhanced by timely release of extracellular acid phosphatases from the plant roots (Shane and Lambers 2005). The water soluble organic-metal complex is mobile within the soil solution and will translocate to PMH zones. The complexed organic-metal compound provides the soil bacteria with a source of carbon and iron, even though it may reside unaltered within the coarse soil matrix until amenable conditions increase bulk soil moisture (Hobbie and Hobbie 2013). When the complexed compound is consumed by the microbe, iron precipitates within EPS or on the soil mineral surface, progressively forming a concentric skin around the PMH zone. These skins are common features and are found on the surface of iron concretions, the face of rhizosphere channels and the top of subsoil layers.

It is important to recognise that the Proteaceae form a relatively ancient lineage extending back to at least the Paleocene (Brundrett and Tedersoo 2018; see Climate chapter) and the bacterial concentration and precipitation of iron has occurred for most of Earth’s history (Konhauser et al. 2017; see Landscape evolution chapter). Thus, the formation of iron concretions likely represents a long-lived process. Further, iron concretions are persistent and protect land surfaces, so iron concretions in soil of the survey area likely represent an extensive temporal record of soil formation that is ongoing.

The Bannar, Hyden and Joseph land systems and upper slopes and crests of the Newdegate land system commonly have an intact sandy surficial horizon overlying a PMH soil layer containing iron nodules: this indicates geologically recent or contemporaneous formation from felsic rocks and siliceous sediments. By contrast, we consider that soils with iron concretions present at the surface are eroding and likely older. Exemplar landforms are breakaways at the margins of the Bannar land system and the shallow ironstone gravel soils on crests of the Hyden land system.

The same biochemical process contributes to soil development on some soils on mafic and ultramafic greenstone rocks. In such situations, the soils develop a surface horizon laden with iron concretions in a red loamy matrix. The extra iron and more easily weatherable basement contribute to faster iron concretion formation and complete cementation of the surrounding iron-rich loamy matrix. These landforms are generally more endowed with prominent breakaways and the Bevon, Bungalbin and Latimore land systems typically display these features. The prolific iron concretion formation also results in gravitational transport (colluviation) of iron concretions and loamy matrix material, forming long gentle slopes extending out from breakaways and containing fine iron concretions in a red loamy matrix. These long and gentle slopes are common as backslope features of the Latimore land system and as gently sloping plains of the Illaara and Monger land systems. The very subdued morphology of the Illaara and Monger land systems suggests great antiquity.

Formation of clay pavements

Researchers who studied eucalypt (mallee) woodland that inhabit duplex soils – akin to soil ecosystems in the south of the survey area – attributed the formation of subsoil clay pavements to the activity of soil bacterial colonies supported by eucalyptus vegetation that supply carbon sources and hydraulically redistribute water and minerals to the PMH of the colonies (Pate and Verboom 2009; Reith et al. 2019). These researchers also identified profuse mycorrhizae – associated with lateral roots of eucalypts – growing in upper soil horizons during the wet winter season. Verboom and Pate (2006b) studied contrasting vegetation and underlying soils across an ecotone that separated proteaceous heath growing on acidic sandy soils with iron oxide concretions from a eucalypt (mallee) woodland growing on sandy duplex soil with an alkaline and calcareous subsoil. This study site lies 26 km south-east of the survey area's south-western corner and contains transitions in soil and vegetation that we commonly saw in the Newdegate land system – mallee vegetation on alkaline sandy duplex soil and heath vegetation on sandy gravel soil. Sandy duplex soils with alkaline and calcareous subsoils are also common across the Nanambinia, Salmon Gums Mallee and Tay zones.

Soil surface features

Several surface features of soils in the southern Goldfields protect them from erosion, increase water infiltration and nutrient capture, and provide niches for seed capture and germination. Surface features take 5 main forms:

- vegetation and leaf litter cover
- biological crusts
- black desert gravel
- biopedogenetic concretions
- stone.

Vegetation and leaf litter

Plants and vegetation communities are the most obvious feature that protect surfaces from erosion, concentrate nutrients and provide niches. These are described in the Vegetation and habitat type ecology chapter. Locations of major and common vegetation–soil associations are described in the Land systems chapter (Volume 2).

Leaf litter prevents erosion by protecting the soil against raindrop impact and saltation by wind. Litter accumulation is usually most dense under trees and shrubs. Further significant protection occurs where leaf litter accumulates against stones, rocks and fallen branches. Accumulations that protect the land surface also form where 'rafts' of litter accumulate as strand lines perpendicular to gradients in extensive sheet flow areas. These form microterraces that accumulate soil fines and seeds, resulting in groves of vegetation forming across slopes in a subdued, terraced landform pattern that prevents or minimises the development of rills and gullies. This pattern instead promotes further gentle sheet flow and subsequent rafting of organic material in a positive feedback mechanism that is constrained by frequency of overland flow.

Biological soil crusts

Biological soil crusts – also named microbiotic soil crusts or cryptogams – are common where the surface soil has a loam or clay texture, and the landform is conducive to water accumulation, often from overland flow. Biological soil crusts are varied and complex symbiotic associations composed of cyanobacteria, mosses, liverworts, fungi (Williams et al. 2018) and likely bacteria (Bates et al. 2011). Lichen and mosses are visible while cyanobacteria and fungi are indistinguishable without magnification.

Biological soil crusts are important components of arid and semi-arid ecosystems. They provide protective cover to the soil and increase surface roughness, thereby stabilising the soil against erosion (Eldridge and Greene 1994), providing niches for seeds and accumulating nutrients. The crusts act as a mulch, reducing evaporation from the soil surface and thereby reducing desiccation and salt concentration. They also increase infiltration rates above that of bare soil (Tongway and Smith 1989; Eldridge and Greene 1994). Some biological components of crusts can photosynthesise, thus increasing net primary productivity and carbon accumulation. The ability of the cyanobacterial and some bacterial components to fix atmospheric nitrogen significantly increases plant-available nitrogen present immediately after rain (Smith et al. 1990).

Biological soil crusts are prominent on plain landforms that have loamy-surfaced calcareous soils, where they commonly occupy greater than 50% of the local land surface. These crusts are common on rises and footslopes, where they occupy a smaller proportion of the land surface, commonly between 30% and 70%. These crusts also persist on shallow soils with a loam surface and an alkaline pH. Where crusts were present in drainage area sites, they occupied greater than 50% of the land surface and tended to have shallow loamy soils, in contrast to the clay soils commonly found in ‘drainage’ landforms. However, note that drainage areas were underrepresented in our site sampling strategy.

Moss is most common in water-accumulating areas surrounding and on rock outcrops. It occasionally covers soil surfaces where water accumulates in drainage depressions of footslopes and loamy plains, where it is associated with calcareous soil types.

A soil surface with a healthy intact biological crust creating good microtopographic features that assist with water retention and niches for seeds. Note the different types and colours of cryptogams

Black desert gravel – biological gravel mantles

In the survey area, alluvial and colluvial plains that have strongly structured and crusting clay soils are often mantled by fine gravels (commonly 2–5 mm) with a dark, or black, surface coat (desert varnish). By contrast, small areas of self-mulching soils within these plains generally lack fine gravel. These black surface concretions are colloquially called 'desert varnish gibber' (DVG). Desert varnish gibber are not transported to these plains from remote land surfaces containing biogenic iron concretions: the soil profiles lack iron concretions; there is no upward-fining sequence typical of recent deposits; the land surfaces lack coarse sand that would indicate erosive concentration. For these reasons, we are unable to justify a geomorphic explanation. Instead, we draw from existing studies and our own observations that support a biochemical mechanism of formation.

Biochemical processes form desert varnishes on rocks of arid environments (Krumbein and Jens 1981; Taylor-George et al. 1983) and extracellular polymeric secretions improve adhesion and incursion of microbial colonies into rock and soil surfaces (Gorbushina 2007). Lingappa et al. (2021) determined that cyanobacterial communities create desert varnish of manganese oxide accumulations to protect against oxidative stress in desert environments in the USA. There, cyanobacteria use manganese as a catalytic antioxidant to prevent oxidative stress caused by intense visible and ultraviolet radiation and variable water availability, a situation comparable to the arid zone of WA and the survey area.

Cyanobacteria require ready access to significant quantities of iron and manganese but cannot cope with high internal concentrations of either, so they are stored as oxide precipitates in cyanobacterial EPS for future use. Cyanobacteria accumulate extraordinary amounts of intracellular manganese and use it in enzymes needed for photosynthesis and protection from oxidative stress caused by reactive oxygen formed during photosynthesis and iron metabolism (Lingappa et al. 2021). Cyanobacteria require iron and molybdenum as electron shuttles and in enzymes needed to fix nitrogen and form ammonium from atmospheric nitrogen. In an environment similar to the survey area, Smith et al. (1990) studied nitrogen-fixing cyanobacteria taken from surface soil vegetated by *Acacia aneura* (mulga) and spinifex and concluded that the surface microbes were widespread and contributed to nitrogen fixation.

We hypothesise that cyanobacteria, which inhabit soil crusts and surficial clay peds of lowland plains, cement those crusts and peds by precipitating iron oxides and manganese oxides within their EPS films and this compound forms the 'desert varnish' surface. Subsequently, the cemented crusts and clay peds progressively weather to fine round DVG that armour the plains' surface. Desert varnish gibber forms preferentially in low landscape positions where the soil and regolith have sufficient concentrations of calcium, iron and molybdenum ions necessary for the enzymes that cyanobacteria create and use during photosynthesis and nitrogen fixation. The landscape position confers regular wetting of the profile, given the arid climate. Water sources include overland flow, capillary rise from deeper within the profile and regolith, and high rates of dew formation, thus permitting high rates of cyanobacteria-mediated photosynthesis and the cascade of biochemical processes that fix iron and manganese as DVG.

Cyanobacteria live within biological soil crusts and within DVG, where they fix nitrogen as ammonium, which leaches into soil during rain and overland flow. Iron-smectite clay minerals common to structured clay soils of lowlands have iron substitution (of structural aluminium) that is subjected to repeated redox cycling by bacteria (Stucki 2006). Such clay minerals in reduced state fix potassium and ammonium cations at structural sites because both have similar ionic radii and charge. This progressively changes the clay structure, converting expanding smectite to the less expansive clay of illite (Stucki 2006), and irreversibly changing gilgai soil to clay plains and pans with much reduced water infiltration. During the survey, we encountered common biological soil crusts and DVG on hard clay dominated by illite proximal to self-mulching clays dominated by smectite and lacking any biological crust and DVG.

These distinct soil-ecosystem units occurred as a mosaic across alluvial plains and were particularly prominent on the Bunyip land system. Figure 5.12 shows the presence of a fine gravel with desert varnish, over partially denuded alluvial plains of the Bunyip land system. Soil profiles are cracking or non-cracking clays whose surface characteristics vary from crusting to strongly pedal self-mulching. The soil surface under perennial grass is more protected from erosion and lies 5–20 cm above the denuded surface. Erosion of the denuded surface preferentially removes unconsolidated soil particles. However, some peds and surface crusts are consolidated by EPS and metal-oxide cements formed by cyanobacteria living within pores and on the surfaces. Over time, these cemented peds and crusts become exposed on the soil surface. Only minor DVG surfaces can develop on the Bunyip land system because overland flow across the level alluvium generates insufficient energy to remove much soil, so only minor, localised microterracing is possible.

Desert varnish gibber develops most abundantly on highly aggregated – but not self-mulching – soils in positions where erosion occurs repeatedly with energy sufficient to remove fine soil material but insufficient to remove DVG and peds cemented by cyanobacterial extracellular polymers. Lower and mid-slope positions of colluvial plains subjected to sheet flow provide the most amenable environment for DVG development because these positions have sufficient water and sunlight, and the soils tend to have strongly-aggregated surface layers. In the southern Goldfields, thick and extensive gravel lags tend to occur on the footslopes of the Coolgardie, Doney, Gundockerta, Helag, Illaara, Monger and Moriarty land systems. The plains of Bunyip, Deadman, Gumland and Helag land systems have minor and moderate lag surfaces.

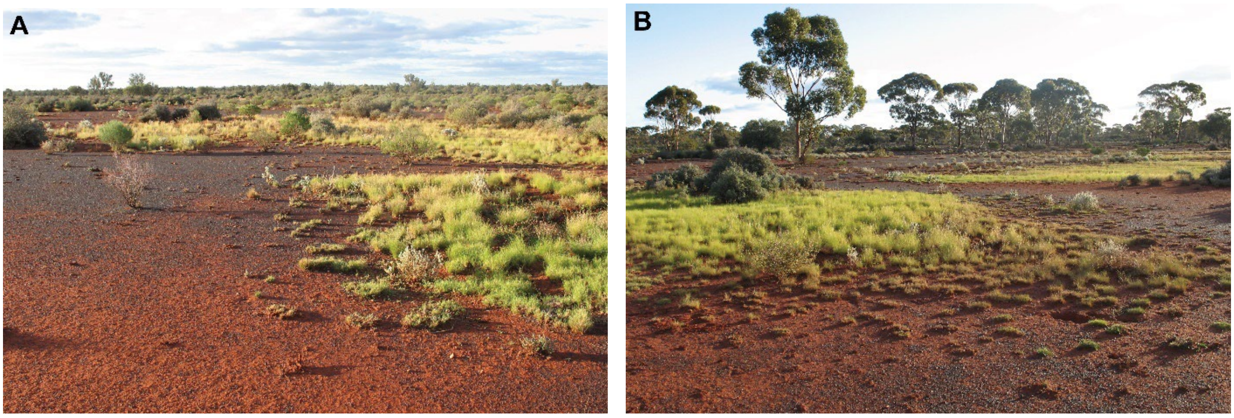


Figure 5.12: Friable non-cracking clay with surface gravel of biotic origin in the Bunyip land system:
A) Denuded surface largely without desert varnish gibber (DVG) in the foreground. Left mid-view shows the localised variability of the protective fine DVG
B) Soil surfaces protected by perennial grasses above the deflated areas with DVG
C) Closeup of DVG, including one large tabular gravel (lower left), and a raised microterrace of vegetated soil, proud of the surface mantled by gravel; note the soil under the grass is red clay

Pedogenetic concretions

Gravel veneers form as erosion removes the soil fines from a surface whose coarse fragments are formed biogenically, such as the processes that form iron and calcium concretions, described above. These surfaces usually have a mantle of rounded gravels and a soil profile packed with rounded gravels and pisoliths. The landscapes formed by gravel-armoured soils are broad, gently convex land surfaces on interfluves, sometimes partly bounded by scarps where the biological cementing mechanism has indurated the substrate or has cemented the gravels to form an ironstone hardpan. Surficial iron-enriched gravels from crests and upper slopes move downslope over time via gravity (colluviation). The gravel accumulates as a surface veneer on mid and lower slope soils that usually lack large accumulations of ironstone gravel in the profile. These colluvial slopes are always proximal to interfluves with ferruginous lag, and are common on the Bannar, Bevon, Cundlegum, Euchre, Greenmount, Hyden and Latimore land systems.

Coarse fragments of geologic origin

Some surficial gravels and stones result from erosion of soil fines and relative accumulation of resistant and unweathered coarse minerals of rock. These occur in 2 distinct situations: most often on hills and upper slopes with skeletal soils; and in situations of lesser erosion potential, such as long colluvial and in situ slopes, where resistant minerals, especially quartz, remain despite otherwise complete weathering of the parent rock, thus permitting deep soil development under a mantle of quartz stones and gravels.

References

Addiscott TM (2010a) ‘Entropy, non-linearity and hierarchy in ecosystems’, *Geoderma, Complexity and Nonlinearity in Soils*, 160:57–63, doi:10.1016/j.geoderma.2009.11.029.

Addiscott TM (2010b) ‘Soil mineralization: an emergent process?’, *Geoderma, Complexity and Nonlinearity in Soils,* 160:31–35, doi:10.1016/j.geoderma.2010.03.016.

Addiscott T (2011) ‘Emergence or self-organization?’, *Communicative and Integrative Biology* 4:469–470, doi:10.4161/cib.4.4.15547.

Albornoz FE, Dixon KW and Lambers H (2021) ‘Revisiting mycorrhizal dogmas: are mycorrhizas really functioning as they are widely believed to do?’, *Soil Ecology Letters,* 3:73–82, doi:10.1007/s42832-020-0070-2.

Andrews SC, Robinson AK and Rodriguez-Quinones F (2003) ‘Bacterial iron homeostasis’ *FEMS Microbiology Reviews*, 27:215–237.

Bates ST, Cropsey GWG, Caporaso JG, Knight R and Fierer N (2011) ‘Bacterial communities associated with lichen symbiosis’, *Applied and Environmental microbiology*, 77(4):1309–1314.

Berg R (1994) ‘A calcium oxalate-secreting tissue in branchlets of the Casuarinaceae’, *Protoplasma,* 183:29–36, doi:10.1007/BF01276810.

Brooksbank K, Veneklaas E, White DA and Carter L (2011) ‘The fate of hydraulically redistributed water in a semi-arid zone eucalyptus species’, *Tree Physiology,* 31:649–658.

Brundrett MC and Tedersoo L (2018) ‘Evolutionary history of mycorrhizal symbioses and global host plant diversity’, *New Phytologist,* 220:1108–1115, doi:10.1111/nph.14976.

Costa OYA, Raaijmakers JM and Kuramae EE (2018) ‘Microbial extracellular polymeric substances: ecological function and impact on soil aggregation’, *Frontiers in Microbiology* 9:1636, doi:10.3389/fmicb.2018.01636.

Crichton RR (2012) 'Chapter 11: Calcium – Cellular Signalling', in Crichton RR (ed) *Biological inorganic chemistry, a new introduction to molecular structure and function*, 2nd edn, pp. 215–228, Elsevier, doi:10.1016/B978-0-444-53782-9.00011-5.

Dart RC, Barovich KM, Chittleborough DJ and Hill SM (2007) 'Calcium in regolith carbonates of central and southern Australia: its source and implications for the global carbon cycle', *Palaeogeography, Palaeoclimatology, Palaeoecology,* 249:322–334.

Davies NS, Shillito AP, Slater BJ, Liu AG and McMahon WJ (2020) 'Evolutionary synchrony of Earth's biosphere and sedimentary-stratigraphic record', *Earth-Science Reviews,* 201:102979, doi:10.1016/j.earscirev.2019.102979.

Douglas and Beveridge (1998) 'Mineral formation by bacteria in natural microbial communities', *FEMS Microbiology Ecology*, 26:79–88.

Eisenhut M (2020) 'Manganese homeostasis in cyanobacteria', *Plants,* 9(1):18, doi:10.3390/plants9010018.

Eldridge DJ and Greene RSB (1994) 'Microbiotic soil crusts: a review of their roles in soil and ecological processes in the rangelands of Australia', *Australian Journal of Soil Research*, 32(3):389–415.

Finlay RD, Mahmood S, Rosenstock N, Bolou-Bi E, Kohler SJ, Fahad Z, Rosling A, Wallander H, Belyazid S, Bishop K and Lian B (2020) 'Biological weathering and its consequences at different spatial levels – from nanoscale to global scale'*, Biogeosciences*, 17:1507–1533.

Franceschi VR and Nakata PA (2005) 'Calcium oxalate in plants: formation and function', *Annual Review of Plant Biology,* 56:41–71, doi:10.1146/annurev.arplant.56.032604.144106.

Gadd GM (1999) 'Fungal production of citric and oxalic acid: importance in metal speciation, physiology and biogeochemical processes', *Advances in Microbial Physiology,* 41:47–92, doi:10.1016/s0065-2911(08)60165-4.

Galloway P, van Gool D, Griffin T, Stuart-Street A, Pathan S and Laycock J (in press) 'Western Australian Soil Groups: a key to classify soils', *Resource management technical report 427*, Department of Primary Industries and Regional Development, Western Australian Government.

Gorbushina AA (2007) 'Life on the rocks – Minireview', *Environmental Microbiology,* 9(7):1613–1631, doi:10.1111/j.1462-2920.2007.01301.x.

Grevenitz P (2006) *The character and genesis of pedogenic calcrete in southern Australia* [PhD thesis], University of Wollongong.

Hassink J, Bouwman LA, Zwart KB, Bloem J and Brussaard L (1993) 'Relationships between soil texture, physical protection of organic matter, soil biota, and C and N mineralization in grassland soils', in Brussaard L and Kooistra MJ (eds) *International workshop on methods of research on soil structure/soil biota interrelationships*, *Geoderma*, 57:105–128.

Hazen RM (2008) 'Mineral evolution', *American Mineralogist*, 93:1693–1720.

Hazen RM (2010) 'Evolution of minerals', *Scientific American,* March 2010:58–65.

Hobbie JE and Hobbie EA (2013) 'Microbes in nature are limited by carbon and energy: the starving-survival lifestyle in soil and consequences for estimating microbial rates', *Frontiers in Microbiology*, 4:324, doi:10.3389/fmicb.2013.00324.

Hopper SD, Lambers H, Silveira FAO and Fiedler PL (2021) 'OCBIL theory examined: reassessing evolution, ecology and conservation in the world's ancient, climatically buffered and infertile landscapes', *Biological Journal of the Linnean Society,* 133:266–296, doi:10.1093/biolinnean/blaa213.

Isbell RF (2016) *The Australian Soil Classification*, 2nd edn, Australian soil and land survey handbook series, Volume 4, CSIRO Publishing, Collingwood, Australia.

Isbell RF and NCST (National Committee on Soil and Terrain) (2021) *The Australian Soil Classification*, 3rd edn, Australian soil and land survey handbook series, Volume 4, CSIRO Publishing, Collingwood, Australia.

IUSS Working Group WRB (2015) *World reference base for soil resources 2014, update 2015, International soil classification system for naming soils and creating legends for soil maps*, World soil resources report no. 106, FAO, Rome.

Jacoby R, Peukert M, Succurro A, Koprivova A and Kopriva S (2017) 'The role of soil microorganisms in plant mineral nutrition – current knowledge and future directions', *Frontiers in Plant Science*, 8:1617, doi:10.3389/fpls.2017.01617.

Jenny H (1941) *Factors of soil formation: a system of quantitative pedology*, McGraw-Hill, New York.

Konhauser KO (1998) 'Diversity of bacterial iron mineralisation', *Earth-Science Reviews,* 43:91-121.

Konhauser KO (2007) *Introduction to geomicrobiology*, Wiley-Blackwell Publishing.

Konhauser KO and Urrutia MM (1999) 'Bacterial clay authigenesis: a common biogeochemical process', *Chemical Geology,* 161:399–413.

Konhauser KO, Planavsky NJ, Hardisty DS, Robbins LJ, Warchola TJ, Haugaard R, Lalonde SV, Partin CA, Oonk PBH, Tsikos H, Lyons TW, Bekker A and Johnson CM (2017) 'Iron formations: A global record of Neoarchaean to Palaeoproterozoic environmental history', *Earth-Science Reviews*, 172:140–177.

Krumbein WE and Jens K (1981) 'Biogenic rock varnishes of the Negev Desert (Israel), An ecological study of iron and manganese transformation by cyanobacteria and fungi', *Oecologia*, 50:25–38, Springer-Verlag.

Lambers H, Mougel C, Jaillard B and Hinsinger P (2009) 'Plant-microbe-soil interactions in the rhizosphere: an evolutionary perspective', *Plant and Soil*, 321:83–115.

Lambers H, Shane MW, Cramer MD, Pearse SJ and Veneklaas EJ (2006) 'Root structure and functioning for efficient acquisition of phosphorus: matching morphological and physiological traits', *Annals of Botany*, 98:693–713.

Lamont BB (2003) 'Structure, ecology and physiology of root clusters – a review', *Plant and Soil*, 248:1–19, Kluwer Academic Publishers.

Liang X and Gadd GM (2017) 'Metal and metalloid biorecovery using fungi', *Microbial Biotechnology*, 10(5):1199–1205, doi:10.1111/1751-7915.12767.

Lingappa UF, Yeager CM, Sharma A, Lanza NL, Morales DP, Xie G, Atencio AD, Chadwick GL, Monteverde DR, Magyar JS, Webb SM, Valentine JS, Hoffman BM and Fischer WW (2021) 'An ecophysiological explanation for manganese enrichment in rock varnish', *PNAS Proceedings of the National Academy of Sciences of the USA,* 118(25):1–8, doi:10.1073/pnas.2025188118.

Lintern M, Anand R, Ryan C and Paterson D (2013) 'Natural gold particles in Eucalyptus leaves and their relevance to exploration for buried gold deposits', *Nature Communications*, 4:2614, doi:10.1038/ncomms3614.

McKenzie NJ and Grundy MJ (2008) 'Soil and landscape processes', in McKenzie NJ, Grundy MJ, Webster R and Ringroase-Voase AJ (eds) *Guidelines for surveying soil and land resources, 2nd edn*, CSIRO Publishing, Australia.

Martin F, Kohler A, Murat C, Veneault-Fourrey C and Hibbett DS (2016) 'Unearthing the roots of ectomycorrhizal symbioses', *Nature Reviews Microbiology*, 14:760–773, doi:10.1038/nrmicro.2016.149.

Navazio L and Mariani P (2008) 'Calcium opens the dialogue between plants and arbuscular mycorrhizal fungi', *Plant Signaling & Behavior*, 3:229–230.

Pal A and Paul AK (2008) 'Microbial extracellular polymeric substances: central elements in heavy metal bioremediation', *Indian Journal of Microbiology*, 48:49–64, doi:10.1007/s12088-008-0006-5.

Pate JS and Verboom WH (2009) 'Contemporary biogenic formation of clay pavements by eucalypts: further support for the phytotarium concept', *Annals of Botany* 103(5):673–685.

Pate JS, Verboom WH and Galloway PD (2001) 'Co-occurrence of Proteaceae, laterite and related oligotrophic soils: coincidental associations or causative inter-relationships?' *Australian Journal of Botany,* 49:529–560.

Penn CJ and Camberato JJ (2019) 'A critical review on soil chemical process that control how soil pH affects Phosphorus availability to plants', *Agriculture*, 9(120):1–18 doi:10.3390/agriculture9060120.

Phillips JD (2009) 'Soils as extended composite phenotypes', *Geoderma* 149:143–151.

Picard A, Gartman A and Girgis PR (2016) 'What do we really know about the role of microorganisms in iron sulfide mineral formation?', *Frontiers in Earth Science*, 4(68), doi:10.3389/feart.2016.00068.

Pylro VS, de Freitas ALM, Otoni WC, da Silva IR, Borges AC and Costa MD (2013) 'Calcium oxalate crystals in eucalypt ectomycorrhizae: morphochemical characterization', *PLOS ONE* 8:e67685, doi:10.1371/journal.pone.0067685.

Reith F, Verboom W, Pate J and Chittleborough D (2019) 'Collaborative involvement of woody plant roots and rhizosphere microorganisms in the formation of pedogenetic clays', *Annals of Botany* 124:1007–1018.

Richardson AE (2001) 'Prospects for using soil microorganisms to improve the acquisition of phosphorus by plants', *Functional Plant Biology*, 28:897, doi:10.1071/PP01093.

Rillig MC, Muller LA and Lehmann A (2017), 'Soil aggregates as massively concurrent evolutionary incubators', *ISME Journal*, 11:1943–1948, doi:10.1038/ismej.2017.56.

Schmalenberger A, Duran AL, Bray AW, Bridge J, Bonneville S, Benning LG, Romero-Gonzalez ME, Leake JR and Banwart SA (2015) 'Oxalate secretion by ectomycorrhizal *Paxillus involutus* is mineral-specific and controls calcium weathering from minerals', *Scientific Reports*, 5:12187, doi:10.1038/srep12187.

Schoknecht N and Pathan S (2013) 'Soil Groups of Western Australia: A simple guide to the main soils of Western Australia', 4th edn, *Resource management technical report 380*, Department of Agriculture and Food, Western Australian Government.

Seifan M and Berenjian A (2019) 'Microbially induced calcium carbonate precipitation: a widespread phenomenon in the biological world', *Applied Microbiology and Biotechnology*, 103:4693–4708.

Shane MW and Lambers H (2005) 'Cluster roots: A curiosity in context', *Plant and Soil*, 274:101–125, Springer.

Sharon S, Salomon E, Kranzler C, Lis H, Lehmann R, Georg J, Zer H, Hess WR and Keren N (2014) 'The hierarchy of transition metal homeostasis: Iron controls manganese accumulation in a unicellular cyanobacterium', *Biochimica et Biophysica Acta (BBA) – Bioenergetics,* 1837:1990–1997, doi:10.1016/j.bbabio.2014.09.007.

Smith GD, Lynch RM, Jacobson G and Barnes CJ (1990) 'Cyanobacterial nitrogen fixation in arid soils of Central Australia', *Microbial Ecology,* 74:79–90, Elsevier.

Stuart EK, Castañeda-Gómez L, Macdonald CA, Wong-Bajracharya J, Anderson IC, Carrillo Y, Plett JM and Plett KL (2022) 'Species-level identity of *Pisolithus* influences soil phosphorus availability for host plants and is moderated by nitrogen status, but not CO_2', *Soil Biology and Biochemistry*, 165:108520, doi:10.1016/j.soilbio.2021.108520.

Stucki JW (2006) 'Chapter 8: Properties and behaviour of iron in clay minerals', in Bergaya F, Theng BKG, Lagaly G (eds) *Handbook of clay science volume 1: Developments in clay science*, Elsevier.

Syed S, Buddolla V and Lian B (2020) 'Oxalate carbonate pathway—conversion and fixation of soil carbon—a potential scenario for sustainability', *Frontiers in Plant Science,* 11:591297, doi:10.3389/fpls.2020.591297.

Taylor-George S, Palmer F, Staley JT, Borns DJ, Curtiss B and Adams JB (1983) 'Fungi and bacteria involved in desert varnish formation', *Microbial Ecology,* 9:227–245, Springer-Verlag.

Tazaki K (1997) 'Biomineralization of layer silicates and hydrated Fe/Mn oxides in microbial mats: an electron microscopical study', *Clay and clay minerals,* 45(2):203–212.

Tazaki K (2006) 'Clays, microorganisms and biomineralisation', in Bergaya F, Theng BKG, Lagaly G (eds) *Handbook of clay science volume 1: Developments in clay science*, Elsevier.

Tecon R and Or D (2017) 'Biophysical processes supporting the diversity of microbial life in soil', *FEMS Microbiology Reviews,* 41:599–623, doi:10.1093/femsre/fux039.

Tongway DJ and Smith EL (1989) 'Soil surface features as indicators of rangeland site productivity', *Australian Rangeland Journal*, 11(1):15–20.

van Gool D, Tille P and Moore G (2005) 'Land evaluation standards for land resource mapping assessing land qualities and determining land capability in south-western Australia', *Resource management technical report 298*, Department of Agriculture and Food, Western Australian Government.

Van Nuland ME, Wooliver RC, Pfennigwerth AA, Read QD, Ware IM, Mueller L, Fordyce JA, Schweitzer JA and Bailey JK (2016) 'Plant–soil feedbacks: connecting ecosystem ecology and evolution', *Functional Ecology*, 30:1032–1042, doi:10.1111/1365-2435.12690.

Verboom WH and Pate JS (2003) 'Relationships between cluster root-bearing taxa and laterite across landscapes in south-west Western Australia: an approach using airborne radiometric and *digital* elevation models', *Plant and Soil*, 248:321–333.

Verboom WH and Pate JS (2006a) 'Bioengineering of soil profiles in semiarid ecosystems: the 'phytotarium' concept. A review', *Plant Soil*, 289:71–102, doi:10.1007/s11104-006-9073-8.

Verboom WH and Pate JS (2006b) 'Evidence of active biotic influences in pedogenetic processes. Case studies from semiarid ecosystems of south-west Western Australia' *Plant Soil*, 289:103–121, doi:10.1007/s11104-006-9075-6.

Wagai R, Kajiura M and Asano M (2020) 'Iron and aluminium association with microbially processed organic matter via meso-density aggregate formation across soils: organo-metallic glue hypothesis.' *Soil,* 6:597–627, doi:10.5194/soil-6-597-2020.

Wang G and Or D (2013) 'Hydration dynamics promote bacterial coexistence on rough surfaces', International Society for Microbial Ecology, *The ISME Journal*, 7:395–404.

Williams AJ, Pagliai M and Stoops G (2018) 'Chapter 19 – Physical and biological surface crusts and seals,' in Stoops G, Marcelino V and Mees F (eds) *Interpretation of micromorphological features of soils and regoliths*, 2nd edn, Elsevier.

6 Vegetation and habitat type ecology

PA Waddell

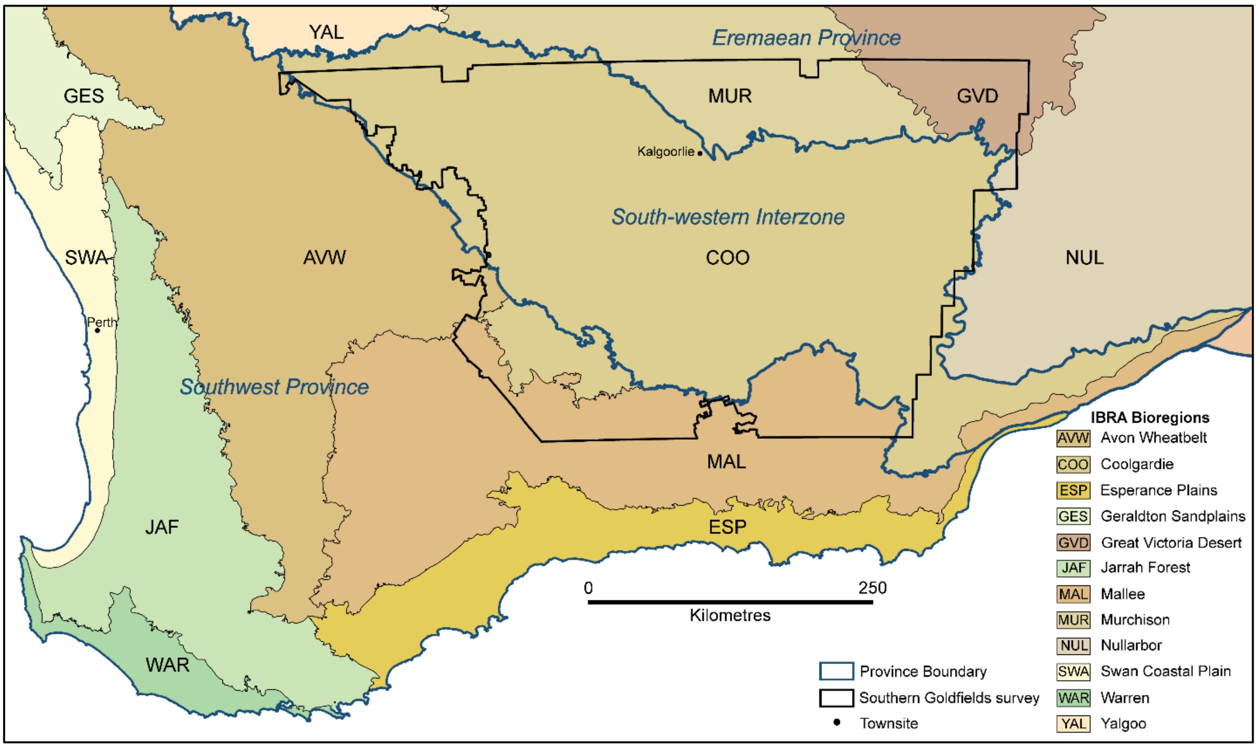
Introduction

This chapter focuses on habitat types, plant community descriptions and the ecology of vegetation communities in the survey area. It commences with a regional overview of the biogeographical regions and soil-landscape zones to provide a broad biogeographic perspective; detailed landscape characteristics are covered in Landscape evolution (Chapter 4) and Land systems (Volume 2, Chapter 7). Terminology is then summarised; first, in terms of vegetation structure and composition; then taxonomic conventions associated with flora conservation; and finally, as indicator terms in relation to grazing. Detailed descriptions of habitat types, which are classified in terms of combinations of landforms, soil types and plant communities, are listed in their broader habitat type groups based on information from 663 inventory sites, augmented with data from 4,611 traverse points.

Regional overview

Regional separation of vegetation types in WA was first undertaken by Diels (1906) and refined by Gardner and Bennetts (1956). In the 1960s, J Beard and M Webb established a vegetation mapping project and a system recognising natural regions and botanical districts for the state (Beard 1980). The phytogeographic regions of WA, as determined by Beard's (1980) vegetation mapping, form the basis upon which many of the state's botanical provinces and districts are still based.

Most of the southern Goldfields survey occurs within the South-western Interzone Botanical Province. The north-east portion falls between Beard's Murchison and Great Victoria Desert regions in the Eremaean Botanical Province and the southern portion is within Beard's Mallee region in the Southwest Botanical Province (Figure 6.1).



Data sources: IBRA bioregions (Environment Australia 2000); botanical provinces (Beard 1980)

Figure 6.1: The bioregions and botanical provinces in and around the survey area

Beard (1990) described the South-western Interzone as ‘Predominantly eucalypt woodlands, becoming open and with saltbush–bluebush understorey on the more calcareous soils. Patches of shrub steppe adjoining the Great Victorian Desert. Scrub–heath and *Casuarina* thickets on sandplains’. He described the Murchison region in the Eremaean Botanical Province as ‘Predominantly mulga low woodland (*Acacia aneura*) on plains, reduced to scrub on hills. Tree steppe of *Eucalyptus* spp. and spinifex (*Triodia basedowii*) on sand plains’ and the Great Victoria Desert region as ‘Mulga low woodland on hardpan soils between dunes; otherwise tree steppe of *Eucalyptus gongylocarpa*, *E. youngiana* and spinifex (*T. basedowii*)’. Beard described the Mallee region in the Southwest Botanical Province as having a general cover of ‘mallee with *Eucalyptus eremophila* the most consistent species. Patches of eucalypt woodland occur on lower ground, and scrub–heath and *Casuarina* thickets on residual plateau soils’.

The pertinent parts of Beard’s mapping for the southern Goldfields were the 1:250,000 map sheets of Kalgoorlie (1972), Boorabbin and Lake Johnston (1976), which formed the basis for the 1:1,000,000 Nullarbor and Swan vegetation maps and accompanying explanatory notes (Beard 1975, 1981).

In 1993–94, the Interim Biogeographic Regionalisation for Australia (IBRA) was developed as a basis for setting priorities to fund additions to the national reserve system. Regionalisation is founded on a landscape-based approach to classify the land surface with a conceptual process model as the basis to understanding and explaining ecological patterns and processes. Patterns were described from the compilation of continental- and regional-scale information on climate, geomorphology, landform, lithology, ecology and characteristic flora and fauna (Thackway and Cresswell 1995). The resulting ‘biogeographic regions’ (bioregions) were regarded as ‘interim’ (formally acknowledged in the title) in recognition that new information would eventually lead to modification.

Most of the survey area lies in the Coolgardie bioregion. Some of the south and south-west is within the Mallee bioregion, and the west is bordered by the Avon Wheatbelt bioregion. To the north-west, but outside the survey area, is the Yalgoo bioregion, which is mentioned because it has some botanical influence. The central northern and north-eastern portions lie within the Murchison bioregion and the Great Victoria Desert, respectively. The Nullarbor bioregion borders the east of the survey area (Figure 6.1, Table 6.1).

The southern Goldfields survey area also aligns closely with the large area referred to as the Great Western Woodlands (Watson et al. 2008). The term ‘Great Western Woodlands’ arose because the southern Goldfield’s location, in the west of Australia, lacked the recognition and status worthy of having the world’s largest and most intact area of Mediterranean-climate woodland (Judd et al. 2008; Watson et al. 2008; Underwood et al. 2009). Most of the Great Western Woodlands occur in the Coolgardie and the Mallee bioregions, with small inclusions of the Avon Wheatbelt and Esperance Plains bioregions. The boundary was determined using satellite data that identified a characteristic ‘eucalypt’ spectral signature found throughout the region (Watson et al. 2008 and references contained therein).

These eucalypt-dominated woodlands, which includes mosaics of mallee, shrubland and grassland, cover nearly 160,000 km^2 (Watson et al. 2008). The southern Goldfields survey area of 151,753 km^2 overlaps much of the same country (Figure 6.2). Except for the southernmost extremities, most of the Great Western Woodlands occurring outside this survey is mapped and described in other rangeland land system surveys: the south-easterly tongue of the Great Western Woodlands, which relates with the Mardabilla subregion (of the Coolgardie bioregion), is covered by the WA Nullarbor survey (Waddell et al. 2010); and the north-westernmost portion of the Coolgardie bioregion is covered by the Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b) and north-eastern Goldfields (Pringle et al. 1994) surveys.

Table 6.1: Regional descriptions derived from IBRA and relevant to the southern Goldfields survey area

IBRA bioregion	IBRA regional description
Avon Wheatbelt	Area of active drainage dissecting a Tertiary plateau in the Yilgarn Craton. Gently undulating landscape of low relief. Proteaceous scrub–heaths, rich in endemics, on residual ferruginised uplands and derived sandplains; mixed eucalypt, *Allocasuarina huegeliana* and jam–York gum woodlands on Quaternary alluvial and eluvial soils. Semi-arid (dry), warm Mediterranean climate. Extensively cleared for agriculture
Coolgardie	Granite strata of Yilgarn Craton with Archean greenstone intrusions in parallel belts. Drainage is occluded. Mallees and scrubs on sandplains associated with ferruginised uplands, playas and granite outcrops. Diverse woodlands rich in endemic eucalypts, on low greenstone hills, valley alluvium and broad plains of calcareous earths. In the west, the scrub is rich in endemic Proteaceae, in the east they are rich in endemic acacias. Semi-arid to arid, warm Mediterranean climate
Great Victoria Desert	Arid active sand-ridge desert of deep Quaternary eolian sands overlying Permian and Mesozoic strata of the Officer Basin. Open woodland of *Eucalyptus gongylocarpa*, *E. youngiana* and mulga over hummock grassland dominated by *Triodia basedowii*. Arid climate, with summer and winter rain
Mallee	Re-defined to include an area from the Coolgardie bioregion between Lake Hope, Forrestiana and Mount Holland, which contains salmon gum and morrel woodlands on greenstone, with smaller areas of mallee and *Acacia* or *Casuarina* thicket on sandplains (Figure 6.1). The south-eastern part of the Yilgarn Craton is gently undulating, with partially occluded drainage. Mainly mallee over myrtaceous–proteaceous heaths on sandy duplex (sand over clay) soils. *Melaleuca* shrublands characterise alluvia, and *Tecticornia* low shrublands occur on saline alluvia. A mosaic of mixed eucalypt woodlands and mallee occurs on calcareous earth plains and sandplains overlying Eocene limestone strata in the east. Semi-arid (dry), warm Mediterranean climate. Extensively cleared for agriculture
Murchison	Mulga low woodlands, often rich in ephemerals, on outcrop hardpan wash plains and fine-textured Quaternary alluvial and eluvial surfaces mantling granitic and greenstone strata of the north of the Yilgarn Craton. Surfaces associated with the occluded drainage occur throughout with hummock grasslands on Quaternary sandplains, saltbush shrublands on calcareous soils and *Tecticornia* low shrublands on saline alluvia. Areas of red sandplains with mallee–mulga woodland over hummock grasslands occur in the east
Nullarbor	Tertiary limestone plain; subdued arid karst features. Bluebush–saltbush shrubland in central areas; low open woodlands of myall over bluebush in peripheral areas, including *Myoporum platycarpum* and *Eucalyptus oleosa* in the east and west. Arid non-seasonal climate
Yalgoo	Interzone between South-western bioregions and Murchison. Characterised by low to open woodlands of *Eucalyptus*, *Acacia* and *Callitris* species on red sandy plains of the western Yilgarn Craton and southern Carnarvon Basin. The latter has a basement of Phanerozoic sediments. Semi-arid to arid, warm Mediterranean climate. Mulga, *Callitris, Eucalyptus salubris* and bowgada open woodlands and scrubs on earth to sandy earth plains in the western Yilgarn Craton. Rich in ephemerals

Source: Environment Australia (2000)

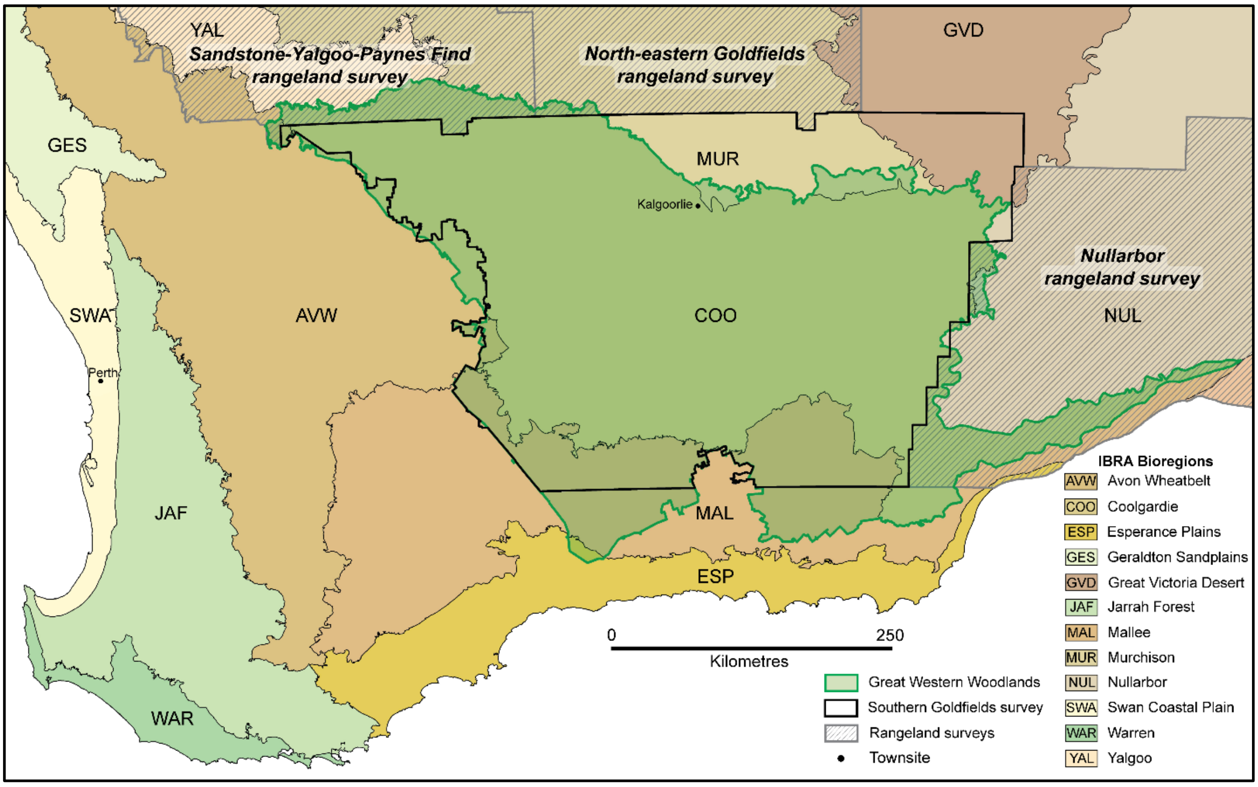


Figure 6.2: Location of the Great Western Woodlands, including the interim biogeographic regions for Australia and overlapping rangeland surveys

Factors influencing vegetation distribution

The region's distinctive landscape and flora are largely the result of interaction between the geology, substrate and low rainfall associated with the semi-arid to arid climate. In the west and centre of the survey area the distribution of Archean granite and granitic gneiss with volcanic and sedimentary successions determines the physiography. In the south-east the geology associated with the Proterozoic Albany-Fraser Orogen exerts a similar influence on the landscape. Furthermore, Eocene marine transgressions (Clarke 1994) have significantly influenced the topography and pedogenesis of the landforms in the south-east. In addition to influencing edaphic characteristics, the geology and topography of the region has partitioned the landscape with landforms such as granitic domes, greenstone hills and salt lakes. These features influence vegetation distribution and physiognomy by interrupting connectivity between landscapes, limiting the spread of fire and creating areas of vegetation with long intervals between fire, leading to variations in community development (O'Donnell et al. 2011a; Gosper et al. 2013b). At a finer scale, some vegetation types and the ecotones between vegetation communities can also act as partial fire barriers. Fire-resistant vegetation communities and sparsely vegetated ecotones can supress fire and thereby affect the structural development of that vegetation community and those communities in their lee (see Sandplain mulga, spinifex hummock grassland [SAMU, #36] and Sandplain crest eucalypt stand [SCES, #42]). Where populations do become disconnected, floristic outliers may result. For example, there are small, isolated populations of *Acacia aneura* (mulga) – which are common in the Murchison bioregion (Eremaean Botanical Province) – north of Lake Lefroy within the Coolgardie bioregion (South-western Interzone).

The onset of aridity since the late Miocene has further influenced the patterning of vegetation (Lowry 1970; Beard 1975; Bowler 1976; Wasson 1982), with temporal, seasonal and spatial variability of rainfall also influencing patterns in floristic composition (Harvey 2014). Increasing rainfall towards the south coast results in some species, such as *Eucalyptus dundasii* (Dundas blackbutt), only occurring in the south. Independently or in combination, these factors are primarily responsible for determining the distribution and growth of the region's vegetation.

Soil-landscape zone classification

Geology and landform influence land characteristics, such as the distribution of soils and natural vegetation. This facilitates mapping and analysis of such characteristics to further subdivide biogeographic regions into soil-landscape zones which provide information at a subregional scale. Zones are described as 'areas defined on geomorphologic or geological criteria, suitable for regional perspectives' (Schoknecht et al. 2004). Soil-landscape zones are based on similar datasets to IBRA (compilation of regional-scale information), but zone boundaries align with amalgamated land system boundaries, where land systems are 'areas with recurring patterns of landforms, soils and vegetation' (Christian and Stewart 1953). Land system and zone boundaries correspond to identifiable natural topographic features, which contrast to some arbitrary boundaries defining IBRA and sub-IBRA regions.

Soil-landscape mapping units are described in a suite of inventory reports, conducted mostly by state and national research and development organisations, and summarised by Schoknecht et al. (2004) and Tille (2006). The spatial data (maps) and attribute information (map-unit descriptions) are stored in spatial digital repositories managed by DPIRD. This publication uses national standards developed by numerous researchers and documented by the National Committee on Soil and Terrain (2009) and expanded by Schoknecht et al. (2004) and Tille (2006), to document information on landform morphology and ecological characteristics specific to the survey area. Providing this detailed natural resource information in accessible digital formats represents a major advancement. The databases enable a consistent presentation and analysis of landform, soil and vegetation data across the state at a range of scales. While this work complements IBRA, the hierarchical nature of soil-landscape information enables data relevant at the property scale to be assessed in a regional, statewide or national context.

Summary of soil-landscape zones in relation to habitat types

Zones are classified within provinces, which are broad scale units that provide an overview of the whole state. These broad scale units are suitable for large scale maps at about 1:5,000,000. There are 6 physiographic provinces that cover the survey area (in order of geographic extent within the survey area): Kalgoorlie, Stirling, Great Victoria Desert, Murchison, Avon and Nullarbor. Within these provinces are 17 soil-landscape zones. Zones are listed according to their geological, geomorphic and spatial relationships with their neighbouring zones. These zones have been extensively revised as a result of this survey. The provinces and zones are described in the Landscape evolution chapter and are summarised below (Figure 6.3).

Kalgoorlie Province

Most of the survey area occurs within the Kalgoorlie Province (Tille 2006) and is based on the Kalgoorlie Province of Bettenay (1983). It correlates with most of the Coolgardie botanical district (Beard 1990) and Coolgardie bioregion (Environment Australia 2000), the south-east of the Yilgarn Craton tectonic unit (Tyler and Hocking 2001), and the south-east of the Yilgarn Plateau Province (Jennings and Mabbutt 1977). It is composed of undulating plains, with some sandplains, hills and salt lakes on Yilgarn Craton granites and greenstones. The Kalgoorlie Province soil-landscape zones within this survey are Youanmi South, Mount Jackson Plains and Hills, Bimbijy Sandplains, Tay, Kambalda and Dundas. Mount Jackson Plains and Hills and Bimbijy Sandplains were described by Tille (2006), and the other zones were first described (Youanmi South, Tay, Dundas) or extensively revised (Kambalda) during this survey.

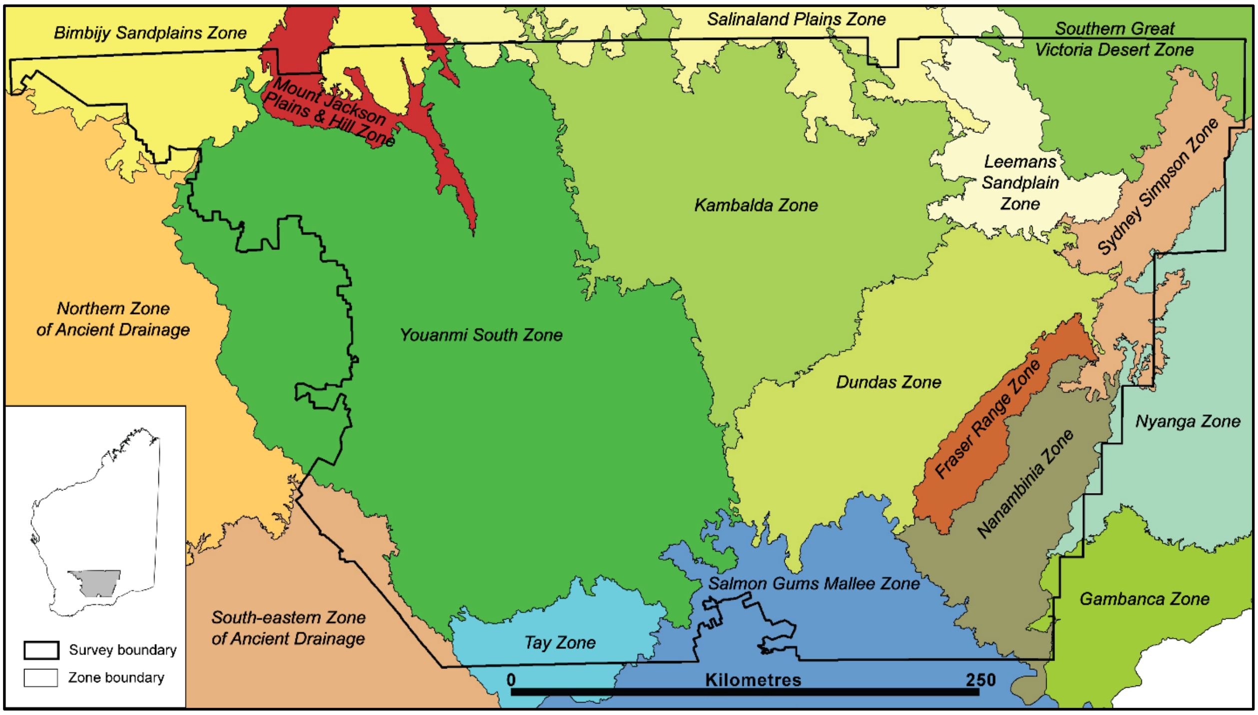


Figure 6.3: Soil-landscape zones in the survey area

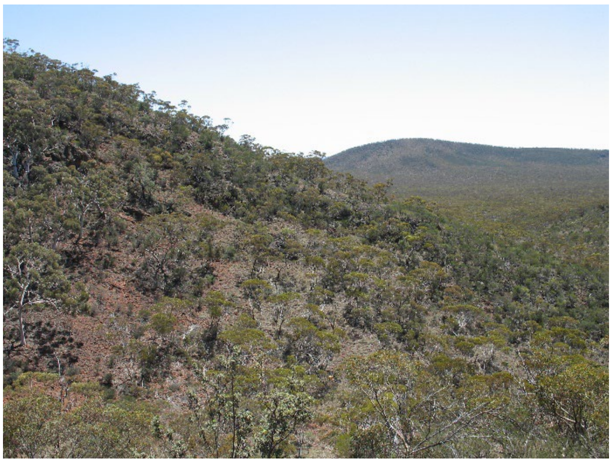
Youanmi South Zone

The west of the survey area is dominated by the Youanmi South Zone. Occupying the western third of the survey, this zone is the largest. The Youanmi South is predominantly gently undulating sandplains with subdued uplands and isolated but locally abundant linear low greenstone hills and occasional granite inselbergs (monadnocks). There is a significant ecological gradient from north to south influencing soil distribution. The sandplain vegetation in the north is spinifex with emergent mallees in yellow deep sand and sandy earth soils. This transitions to acacia–allocasuarina–melaleuca scrub–thickets on in situ granite-derived sandplain soils consisting of yellow deep sand sometimes with ironstone gravels, and various ironstone gravelly soils through the central part. These vegetation and soil complexes are also interspersed throughout the north and south of the zone in lesser prominence. The vegetation and soil transitions again in the south so that the southernmost part of the zone is populated by mallee-dominated heathlands on ironstone gravelly pale deep sand, sandy ironstone gravel and sandy duplex soils (duplex soils have a distinct texture contrast between the topsoil and the subsoil, and the subsoil texture is more clayey). Dissecting the sandplains are broad valleys draining to occluded playas and chains of salt lakes. In the valleys, the soils are yellow sandy and loamy earths, calcareous loamy earths sometimes with gravel, and various alkaline sandy duplexes. Salt lake soils and other saline soils occupy the lowest landscape positions. Colluvial slopes and valley floors are dominated by mixed eucalypt woodland (with groves of melaleucas) over non-halophytic shrubs. Halophytic shrublands are largely restricted to poorly drained saline flats and the margins of playas and salt lakes.

Sandplain heathland in the Youanmi South Zone

Mount Jackson Plains and Hills Zone

North of the Youanmi South Zone lies the iron-rich hills and undulating plains of the Mount Jackson Plains and Hills Zone. The prominent, banded iron formation (BIF) of Bungalbin (Helena and Aurora Range) dominates the southern portion and the crests and upper slopes of the ranges are dominated by rock, shallow and stony soils. Abundant secondary iron concretions mantle some BIF (see Soils chapter) and in these areas, soils are mostly shallow loamy gravel over ferruginous duricrust. Some BIF surfaces have been overprinted with calcareous pedogenetic material to form calcareous stony and calcareous ironstone gravel soils. The soils of slopes and footslopes of the range primarily consist of stony soil and loamy gravel on gradients, with various red shallow loam soils on footslopes grading to hardpan shallow loams and red loamy earths on adjacent plains. On the range and nearby surrounds, woodlands with *Eucalyptus capillosa* (inland wandoo) and *E. ebbanoensis* subsp. *ebbanoensis* over grass tussocks of *Neurachne annularis* are common, with *Banksia arborea* (Yilgarn dryandra) more common on the ferruginous ridge crests. Other BIFs support allocasuarina scrub–thickets, and these usually form calcareous pedogenetic overprinting. The broad valley floors between uplands support *E. salmonophloia* (salmon gum) and *E. salubris* (gimlet) woodlands over chenopod-dominated understoreys.



Hillslope of Bungalbin (Aurora Range) supporting *Eucalyptus capillosa* and *E. ebbanoensis* subsp. *ebbanoensis* woodland over grass tussocks of *Neurachne annularis* in the Mount Jackson Plains and Hills Zone

Bimbijy Sandplains Zone

The north-west of the survey area occurs in the Bimbijy Sandplains Zone. This surrounds the north of the Mount Jackson Plains and Hills Zone. The Bimbijy Sandplains is dominated by sandplains over granitic rocks of the Yilgarn Craton. Soils of this zone within the survey area are predominantly yellow deep sand, with minor yellow and brown sandy duplex and shallow sand soils. Sandplains to the north become redder and increasingly consist of red deep sand and sandy earth soils, which transition near granite outcrops to red shallow sand and loam soils. Northern sandplains typically support spinifex grasslands, while southern sandplains support mallee woodland over spinifex, with acacia–allocasuarina thickets on gravelly sand sheets. Sheetwash plains containing red loamy earth and hardpan shallow loam soils drain to infrequent salt lake chains with saline soils. Woodlands of the mallee *Eucalyptus loxophleba* subsp. *lissophloia* (smooth-barked York gum), *Acacia aneura* (mulga) and acacia thickets occupy the sheetwash plains. These transition into lowland habitat types that support *E. salmonophloia* (salmon gum) and *E. salubris* (gimlet) woodlands (with some mallee and acacia scrub) on alkaline red loamy duplex and red clay soils, with halophytic shrublands adjacent to lake country on saline soils and non-cracking clay soils.

Sand sheet on edge of sandplain supporting a mallee woodland of *Eucalyptus concinna* (Victoria Desert mallee) over spinifex in the Bimbijy Sandplains Zone

Tay Zone

Further south-west and south of the Youanmi South Zone is the Tay Zone. Upper catchment interfluves consist of gently undulating plains overlying deeply weathered granites with alkaline shallow sandy duplex soils that are vegetated by diverse mallee low woodland. Parts were affected by Eocene marine transgression and have sandy and calcareous sediments concentrated in the broad valleys. Similar low mallee vegetation communities occupy these areas which contain shallow sandy duplex soil that is generally more calcareous, and often contains abundant calcareous pedogenetic concretions. The zone drains to occluded salt lakes in the lowest landscape with extensive eolian calcareous and gypsiferous dunes forming near the lakes, and sand sheets with pale or yellow gravelly sand soils vegetated by diverse heath.

Undulating plain supporting a low mallee woodland of *Eucalyptus platycorys* (Boorabbin mallee) and *E. rigidula* (stiff-leaved mallee) over heath on a sandy duplex soil in the Tay Zone

Kambalda Zone

The Kambalda Zone occupies the centre of the survey area and predominantly consists of greenstone hills and ranges, granitic hills and rises and the intervening broad, level to undulating plains between the upland areas. Soils vary according to the diverse geology and are often highly calcareous, in contrast to the comparatively uniform yellow sandplains with generally acidic pH ranges of the granite-dominated Youanmi Terrane, which borders the Kambalda Zone's western margin. The broad, sheetwash plains are dominated by calcareous loamy earth soils often with gravel, and calcareous clay loam soils become more prevalent on the lower slopes of sheetwash plains. Further concentration of carbonates during pedogenesis sometimes forms calcrete hardpans within the soil profiles, so that some eucalypt vegetation communities grow on calcareous shallow loam soils often with gravel.

The geology coincides with vegetation composed of *Eucalyptus salmonophloia* (salmon gum) and *E. salubris* (gimlet) dominated woodlands over either chenopod- or eremophila-dominated understoreys. Chenopod-dominated understoreys are commonly associated with alkaline red loamy duplex soils that are usually calcareous at depth. In contrast, eremophila-dominated understoreys tend to occur on red loamy earth and loamy duplex soils, which are not alkaline or only alkaline at great depth. Acacia shrublands frequently dominate the hills, ranges and stony rises that commonly contain calcareous, loamy, shallow and stony soils. The lower slopes have calcareous shallow loam and loamy earth soils.

Broad valley floor supporting *Eucalyptus salmonophloia* (salmon gum) and *E. salubris* (gimlet) woodland over low chenopod shrubland in the Kambalda Zone

The Kambalda Zone is characterised by sequential episodes of erosion emanating from the lowest base level to the upper slopes, and these episodes are controlled by landscape knick-points that set the local base level at a subcatchment scale. A consequence of this stepwise regional erosive lowering is that younger subcatchments, whose unweathered rocky headwaters generate fresh run-off, form footslopes and valleys with fresh and brackish minor ephemeral rivers and terminal swamps and lakes. Conversely, older subcatchments whose headwaters are more deeply weathered form salt lake chains. Major trunk valleys fed by both 'forms' of subcatchment are occupied by large salt lakes with extensive hydroeolian landforms. Distinct soil and vegetation communities result from these divergent allochthonous (imported) sources. Where fresh and brackish waters dominate in lower landscape termini, the dominant soils are cracking clays that are vegetated by gimlet woodland outside of swamp landforms and *Duma florulenta* (lignum) in swamps. Where salts accumulate, the lowest landscapes are frequented by prominent, endoreic salt lakes which generally drain eastwards (see Landscape evolution chapter). The salt lakes and adjacent saline alluvial plains support diverse halophytic communities on saline soils, calcareous clay loam and clay soils, often with a gypsic and saline subsoil. Similar soils also persist remote from salt sources and in these cases only the deeper subsoil is gypsic and saline, and common vegetation is *Eucalyptus campaspe* (silver gimlet), *E. ravida* and/or *E. salubris* woodland. Windblown gypsum deposits form dunes with sparse vegetation on lake beds and at the eastern margin of lakes. Adjacent to, and derived from, the lake systems are elevated, more xeric (very dry) landforms of eolian lunettes and sand sheets, with yellow deep sand and calcareous sandy earth soils, sometimes with gravel. These support mallee eucalypts over spinifex hummock grasses and non-halophytic shrubs.

Dundas Zone

South of the Kambalda Zone lies the Dundas Zone, which occurs entirely within the lower central easterly portion of the survey area. It consists of very gently undulating plains with a thin veneer of fine, sandy marine sediments over an Archean–Proterozoic suture zone whose surface was levelled by wave ravinement during a sequence of Eocene and Miocene marine transgressions (see Climate and Landscape evolution chapters). Soils are dominated by calcareous materials and on the plains are calcareous shallow loam and loamy earth soils, sometimes with gravel. Hills and rises of shallow crystalline basement rock and occasional outcrops of spongolite sedimentary sequences contain various shallow and stony soils that have mostly been overprinted with calcareous accessions, although some rocky uplands currently being eroded are not calcareous and have stony and shallow loam soils. Drainage to and within the lowest landscape areas is subdued and occluded, and salt lake chains are present with saline soils. Sand dunes and sand sheets are common to the south-east of salt lakes. Their source material originates from surface swash processes in the salt lakes and subsequent eolian removal, and they typically have calcareous gravelly deep sand and yellow deep sand soils. The plains predominantly support *Eucalyptus oleosa* subsp. *oleosa* (giant mallee) and *Melaleuca* spp. (boree) woodland over understoreys dominated by *Cratystylis conocephala* (false bluebush). The Lake Cowan salt lake chain denotes the westerly zone margin. This supports chenopod communities along its lacustrine surfaces and mallee eucalypts over spinifex hummock grasses on lunettes and sand sheets. From south-west to north-east, extensive lake beds become smaller connected lakes and then isolated playas.

Level, calcareous loamy plain supporting a *Eucalyptus oleosa* subsp. *oleosa* (giant mallee) woodland over *Atriplex vesicaria* (bladder saltbush) and *Cratystylis conocephala* (false bluebush) in the Dundas Zone

Stirling Province

As described by Tille (2006), the Stirling Province is based on the Stirling Province of Bettenay (1983). It correlates with most of the Eyre and Roe botanical districts (Beard 1990), and the southern portion of the Yilgarn Plateau Province (Jennings and Mabbutt 1977). Stirling Province has gently undulating plains on Albany-Fraser Orogen basement, with minor Yilgarn Craton granites, overlain by marine sediments through which isolated hills of resistant rock protrude. The soil-landscape zones within this survey are the Salmon Gums Mallee, Fraser Range and Nanambinia zones.

Salmon Gums Mallee Zone

The Salmon Gums Mallee Zone occupies the central southern area and margin of the survey. This zone consists of level to gently undulating plains of Tertiary sediments over Proterozoic granites and gneiss. Drainage tracts are few and indistinct in the north and contain infrequent closed depressions and drainage foci that become increasingly common towards the south (outside the survey area). Soils are predominantly alkaline and have a characteristic fine sand fraction. The dominant soils are alkaline shallow sandy duplex and calcareous loamy earth soils, often with calcareous gravels and concretions, with some alkaline grey or red shallow loamy duplex, deep sand and salt lake soils. Vegetation consists of woodland mosaics of *Eucalyptus oleosa* subsp. *oleosa* (giant mallee), merrit (now consisting of the subdivided taxa from the *Eucalyptus flocktoniae* Complex: *E. flocktoniae* subsp. *hebes* and *E. urna* [Nicolle and Conran 1999]) and *E. salmonophloia* (salmon gum), with mallee and scrub–heath.

Level plain supporting a mixed eucalypt woodland of *Eucalyptus oleosa* subsp. *oleosa* (giant mallee) with *E. cylindrocarpa* (woodline mallee) and *E. lesouefii* (Goldfields blackbutt) over *Melaleuca sheathiana* (boree) and a non-halophytic shrub understorey in the Salmon Gums Mallee Zone

Fraser Range Zone

The Fraser Range Zone lies in the south-east of the survey area and forms the south-east border of the Dundas Zone. It is named after the prominent rolling hills and rises associated with Fraser Range, and characterised by Proterozoic metamorphic rocks, mostly of gabbroic origin, associated with the Albany-Fraser Orogen. The north-eastern half is characterised by gently undulating pediments and the south-western half has more undulating landforms of rolling rises to hills. The soils display a similar division to the landform, with the north-east dominated by shallow soils over rock and calcrete, and shallow loams and clays (also mostly calcareous). The south-western half has much greater relative relief with a commensurate increase in soil diversity. Hill crests and ridges contain rock, and shallow and stony soils that are often calcareous, while accumulating areas of mid and lower slopes contain alkaline red loamy duplex, calcareous shallow loam and loamy earth soils, and various clay soils usually calcareous at depth. Stony hills support scattered *Allocasuarina huegeliana* (rock sheoak) and *Pittosporum angustifolium* (native willow) with *Dodonaea adenophora* and *D. microzyga* low scrubland between. Mixed mosaics of *Dodonaea* spp. low scrub or *Triodia* spp. (spinifex) with mallee occur on lower slopes. Footslopes and adjacent plains support eucalypt forest, typically consisting of *E. dundasii* (Dundas blackbutt) and groves of melaleuca, or *E. oleosa* subsp. *oleosa* (giant mallee) dominated woodland over *Atriplex* spp. (saltbush) or *Cratystylis conocephala* (false bluebush) dominated understoreys.

Hillslope on Fraser Range with a dense covering of *Ptilotus obovatus* (cotton bush) in the Fraser Range Zone

Nanambinia Zone

The Nanambinia Zone is based on the Harms vegetation system (Beard 1975) and occupies the south-east of the survey between Fraser Range and Balladonia Roadhouse. It is typified by undulating plains on shallow calcareous sediments over Proterozoic granite and gneiss of the Albany-Fraser Orogen. The soils are calcareous gravelly loamy earth and shallow loam, with some calcareous gravelly sandy earth and deep sand soils. The plains are infrequently punctuated by granite outcrop or closed depressions that may sometimes contain small salt lakes. The soils are various shallow sandy and loamy duplexes, red loamy earth (often calcareous) and salt lake soils. The zone supports a woodland mosaic of *Eucalyptus oleosa* subsp. *oleosa* (giant mallee), merrit (now consisting of the subdivided taxa from the *Eucalyptus flocktoniae* Complex: *E. flocktoniae* subsp. *hebes* and *E. urna* [Nicolle and Conran 1999]) and *E. transcontinentalis* (redwood) woodland over either non-halophytic- or chenopod-dominated understoreys. *E. salubris* is common on heavier-textured soils.

Closed depression dominated by *Westringia rigida* within gently undulating plain supporting *Eucalyptus oleosa* subsp. *oleosa* (giant mallee) woodland over *Cratystylis conocephala* (false bluebush) in the Nanambinia Zone

Great Victoria Desert Province

The Great Victoria Desert Province is based on the Gunbarrel Basin tectonic unit (Tyler and Hocking 2001). It is in the southern arid interior to the south of the Canning and Western Desert Ranges provinces (Tille 2006 and references therein), north of the Nullarbor and Tarcoola-Quondong provinces (Northcote 1983), and east of the Murchison, Ashburton, Officer and Paterson-Yeneena provinces (Tille 2006 and references therein). This province includes the Great Victoria Desert and the southern portions of the Great Sandy and Gibson deserts. It is dominated by sandplains and dunes, with some undulating plains and uplands on sedimentary rocks. The soil-landscape zones associated with the Great Victoria Desert Province and within this survey are the Southern Great Victoria Desert and Sydney Simpson zones.

Southern Great Victoria Desert Zone

The Southern Great Victoria Desert Zone is dominated by undulating sandplains and dunes, with infrequent gravelly plains and calcrete plains, on sedimentary rocks of the Gunbarrel (and underlying Officer) Basin. The south-west of the zone is in the north-east of the survey area. This part of zone is atypical because it is dominated by yellow deep sand – north of the survey area, the zone is dominated by red deep sand and sandy earth soils, with some red loamy earth and hardpan shallow loam soils. Vegetation in the survey area is dominated by spinifex grasslands with mallee (for example, *Eucalyptus youngiana*) and scrub, and some *Acacia aneura* and eucalypt (for example, *E. gongylocarpa*) woodlands.

Swale between dunes in a dunefield on yellow deep sand supporting scattered *Eucalyptus gongylocarpa* (marble gum) and *E. youngiana* (large-fruited mallee) among spinifex grassland in the Southern Great Victoria Desert Zone

Sydney Simpson Zone

The south-western part of the Sydney Simpson Zone occupies the far north-east of the survey area. The zone is characterised by gently undulating calcareous plains overlain by sand sheets with occasional dunes over Proterozoic gneiss and volcanic rocks of the Albany-Fraser Orogen. Soils are dominated by calcareous gravelly sandy and loamy earths and shallow loam soils. Less common soils are red deep sand and sandy earth, and shallow sand and loam soils near rock outcrops. In the survey area, vegetation is dominated by *Eucalyptus concinna* (Victoria Desert mallee) woodlands over *Triodia scariosa* (spinifex) and some *Acacia aneura* shrublands.

Sand sheet over calcareous loamy earth supporting a mallee *Eucalyptus concinna* (Victoria Desert mallee) woodland over spinifex in the Sydney Simpson Zone

Murchison Province

As described by Tille (2006), the Murchison Province is based on the Murchison Province of Bettenay (1983) and the bulk of the Austin botanical district (Beard 1990). It correlates with the Murchison and Yalgoo IBRA regions (Environment Australia 2000) and the north-central portion of the Yilgarn Plateau Province (Jennings and Mabbutt 1977). This province has a very gently undulating surface of sandplains and hardpan sheetwash plains underlain by granite and greenstone rocks. The soil-landscape zones within this survey are the Salinaland Plains and Leemans Sandplain.

Salinaland Plains Zone

The central portion of the survey's northern border occurs along the southern margin of the Salinaland Plains Zone which also delineates the south of the Murchison Province (as described by Tille 2006) and the entire northern boundary of the Kambalda Zone. The Salinaland Plains Zone consists of sandplains with hardpan sheetwash plains, some mesas, stony plains and salt lakes, on granite and some greenstone rocks. The sandplains contain red deep sand and sandy earth soils. The sheetwash plains are dominated by hardpan shallow loam and red loamy earth soils, with some red shallow sandy duplex soils. Rock outcrops have shallow and stony soils and are surrounded by red shallow sand and loam soils. Salt lake soils occupy the landscape sumps. The vegetation is dominated by *Acacia aneura* (mulga) shrublands with spinifex grasslands and some halophytic shrublands. Towards the south, the mulga shrublands transition to eucalypt–mulga woodland as eucalypts progressively become dominant and red loamy duplex soils replace hardpan shallow loam soils.

Level plain with a shallow loam over red–brown hardpan supporting an *Acacia aneura* (mulga) tall shrubland in the Salinaland Plains Zone

Leemans Sandplain Zone

This zone borders the eastern margin of the entire Salinaland Plains Zone and the north-east of the Kambalda Zone in the survey area. It corresponds with the Leemans Sandplain Zone of Jennings and Mabbutt (1977). It is narrow and lies between the Salinaland Plains and the Southern Great Victoria Desert zones. In the survey area, its southern margin is also bordered by the Dundas and Sydney Simpson zones. The Leemans Sandplain is dominated by sandplains over granitic rocks, interspersed with some mesas, gravel plains and salt lakes. There are red sandy and loamy earth soils, and some red deep sand, hardpan shallow loam and calcareous loamy earth soils. Soils become more yellow than red towards the transition to the Dundas and Sydney Simpson zones but are otherwise similar. The vegetation is dominated by mallees (for example, *Eucalyptus concinna*, *E. youngiana*), mulga shrublands and spinifex grasslands with *E. gongylocarpa* (marble gum). Halophytic shrublands are restricted to the footslopes of mesas, saline stony pavements and salt lakes.

Sandplain of red deep sand supporting a spinifex-dominated acacia shrubland with *Eucalyptus concinna* (Victoria Desert mallee) in the Leemans Sandplain Zone

Avon Province

The Avon Province is based on the Avon Province of Bettenay (1983). As described by Tille (2006), it correlates with most of the Avon and Dale botanical districts (Beard 1990), the south-west of the Yilgarn Craton tectonic unit (Tyler and Hocking 2001) and the south-west of the Yilgarn Plateau Province (Jennings and Mabbutt 1977). The Avon Province incorporates much of the Avon Wheatbelt bioregion, as well as the western portion of the Mallee bioregion and eastern portions of the Jarrah Forest and Warren bioregions. It has a gently undulating surface of sandplains and ferruginous divides on Yilgarn Craton granites and gneisses, with limited areas of metasedimentary and metavolcanic rocks, and minor dolerite dykes. The soil-landscape zones within this survey are the South-eastern Zone of Ancient Drainage and a very marginal incursion of the Northern Zone of Ancient Drainage.

South-eastern Zone of Ancient Drainage

The South-eastern Zone of Ancient Drainage occupies the far western margin of the survey area. Gently undulating plains with salt lake chains in the main valleys with duplex and ironstone gravel soils on the uplands and areas of prominent granitic outcrop characterise this zone. Mallee woodland is common to alkaline sandy duplex soils, with proteaceous scrub–heath on pale or yellow deep sand sometimes with ironstone gravel, and ironstone gravel soils. The valley floors support *Eucalyptus salmonophloia* (salmon gum), *E. salubris* (gimlet) and morrel (*E. longicornis*, *E. melanoxylon*) woodlands and halophytic shrublands on calcareous and red loamy earth, alkaline red shallow loamy duplex and saline soils.

Loamy plain supporting a mixed eucalypt woodland of *E. melanoxylon* (black morrel), *E. salicola* (salt gum) and *E. urna* over *Atriplex vesicaria* (bladder saltbush) and *Ptilotus obovatus* (cotton bush) in the South-eastern Zone of Ancient Drainage

Northern Zone of Ancient Drainage

The Northern Zone of Ancient Drainage is only just present in the north-western corner of the survey area, as such it is only minimally described. Within the survey area it consists of gently undulating terrain, with gravelly upland sandplain and sheetwash plain draining to a salt lake (outside the survey area). The sandplains support myrtaceous–proteaceous scrub–heath on yellow deep sand and ironstone gravel soils. Sheetwash plains have shallow loam and loamy earth soils that support mallee woodlands of *Eucalyptus loxophleba* subsp. *lissophloia* (smooth-barked York gum) with *Acacia acuminata* (jam).

Gravelly upland sandplain supporting *Callitris* spp. and *Allocasuarina acutivalvis* subsp.*acutivalvis* scrubland over myrtaceous–proteaceous heath in the Northern Zone of Ancient Drainage

Nullarbor Province

As described by Tille (2006), Nullarbor Province consists of a combination of the Bunda Plateau and Roe Plain sections (Jennings and Mabbutt 1977). It corresponds with the Nullarbor Province (Northcote 1983) and the Nullarbor environmental association mapped in South Australia by Laut et al. (1977) and referenced by Tille (2006). This province covers most of the Eucla botanical district as well as eastern tongues of the Coolgardie and Roe districts (Beard 1990). The province is characterised by limestone and calcrete plains. Soil-landscape zones within this survey are Nyanga and Gambanca.

Nyanga Zone

The eastern border of the survey area is closely aligned with the western margin of the Nyanga Zone of the Nullarbor Province (as described by Tille 2006), which roughly equates to the western extent of the Eucla Basin (Lowry 1970). The zone is characterised by calcrete plains over Miocene limestone. Soils are mainly calcareous gravelly sand, and sandy and loamy earth soils, with some calcareous loamy earth and shallow loam soils that are often gravelly. The vegetation predominantly consists of mosaics of *Eucalyptus oleosa* subsp. *oleosa* (giant mallee) and *E. gracilis* (white mallee) woodlands over mixed scrub or chenopod understoreys; *Acacia papyrocarpa* (western myall) and/or *Casuarina pauper* (black oak) woodlands over chenopods; or *E. oleosa* subsp. *oleosa* and *E. concinna* (Victoria Desert mallee) over spinifex.

Level calcareous loamy plain supporting a scattered mallee woodland of *Eucalyptus oleosa* (giant mallee) with *Acacia papyrocarpa* (western myall) over *Cratystylis conocephala* (false bluebush) and mixed chenopods in the Nyanga Zone

Gambanca Zone

The south-easternmost part of the survey area is along the edge of the Gambanca Zone in the south-west of the Nullarbor Province. The zone is based on the Nanambinia vegetation system, including the eastern tongue of the Coolgardie vegetation system (Beard 1975). The Gambanca Zone consists of undulating calcrete plains on the Eocene and Miocene limestones of the Eucla Basin. Soils are primarily calcareous shallow loam and loamy earth soils that are often gravelly, and some red loamy earth soils. The plains predominantly support *Eucalyptus oleosa* subsp. *oleosa* (giant mallee) and merrit (now consisting of the subdivided taxa from the *Eucalyptus flocktoniae* Complex: *E. flocktoniae* subsp. *hebes* and *E. urna* [Nicolle and Conran 1999]) woodlands with scrub or occasional saltbush.

Calcrete plain supporting a mallee woodland of mixed *Eucalyptus* species over mixed shrubs and sedges in the Gambanca Zone

Habitat types as ecological units

The interrelationships between the physical environment and its plant communities can be described by classifying sampling points (inventory sites) into habitat types. Habitat types are classified in terms of combinations of landforms, soil types and plant communities. They closely resemble the 'ecological site' of the Society for Range Management (1991) and the habitat of Tinley (1991). In previous rangeland surveys, habitat types have been referred to as 'pasture types' (Payne et al. 1987), 'pasture lands' (Payne et al. 1988), 'vegetation types' (Curry et al. 1994), 'site types' (Pringle et al. 1994) and 'habitat types' (Payne et al. 1998b; Waddell et al. 2010). Habitat type was chosen because it most accurately fits the ecological classification below and has relevance to those not necessarily familiar with rangeland survey or pastoral production systems.

Habitat types are generally referred to by their land surface, dominant taxon and dominant vegetation stratum, and given an appropriate four-letter code (for example, PEEW: Plain eucalypt, eremophila woodland). Many habitat types identified in this survey are distinguished specifically by their dominant vegetation because within many woodland associations, the understorey remained similar while the dominant species forming the upper canopy differed across the survey area.

Habitat types are described within broader habitat groups to aggregate ecologically similar types. Habitat types within a 'habitat type group' are in topographically comparable positions.

Habitat types are described in terms of:

- general information (physical environment, soils, distribution patterns, general ecology)
- vegetation physiognomy (growth form, projected foliar cover) and composition (by stratum)
- patterns of variation influenced by disturbance events (grazing, fire)
- gradational associations
- land system representation (a habitat type is defined as being 'dominant' on a land system if it occurs on 60% or more of the area, as 'major' where it occurs on 20–60%, and 'minor' where it occurs on less than 20% of the land system).

Soil classification system

The soil types mentioned are categorised using the WA Soil Group classification (Galloway et al. in press). Soil groups describe and name the soils using recognisable soil morphological features.

Vegetation structure

Growth form and height classes

The definitions used to describe growth form for structural formations are outlined in Table 6.2.

Table 6.2: Definition of vegetation growth forms

Growth form	Description
Tree	A woody plant over 2 m high, with a single stem to at least 1.3 m, including single stem eucalypts
Mallee	A multi-stemmed eucalypt, with multiple stems arising from a lignotuber
Tall shrub	A perennial woody plant over 2 m tall with more than one main branch below 1.3 m
Mid shrub	A perennial woody plant between 1 m and 2 m in height
Low shrub	A perennial woody or herbaceous plant lower than 1 m in height
Perennial grass	A member of the Poaceae family, usually persisting for at least 2 years
Annual	A short-lived plant usually persisting for less than 2 years
Other plant form	Plant such as climbers, ferns, herbs, mistletoes, rushes and sedges
Climber (vine)	Twining, winding or sprawling plants, usually with a woody stem
Fern	Plant characterised by large and usually branched leaves (fronds), herbaceous and terrestrial to aquatic; spores in sporangia on the leaves
Herb (forb)	Seasonally dependent, weakly facultative perennial, generally less than 0.5 m high, usually persisting for less than 2 years
Mistletoe	Plant with roots attached to the aerial portions of other plants
Rush	Herbaceous, usually perennial, erect monocotyledon that is neither grass nor sedge
Sedge	Herbaceous, usually perennial, erect plants generally with a tufted habit and from the family Cyperaceae (true sedges) or Restionaceae (node sedges)

Note: Growth forms were based on Specht (1970); Muir (1977); Hnatiuk et al. (2009); and NVIS (2017).

Good condition *Eucalyptus salubris* (gimlet) woodland over *Cratystylis conocephala* (false bluebush) shrubland with abundant *Atriplex vesicaria* (bladder saltbush) and *Austrostipa elegantissima* (feather speargrass)

Vegetation formations

The definitions used to describe the vegetation formations and strata are outlined in Table 6.3.

Table 6.3: Definition of vegetation formations

Formation	Description
Woodland	Dominant stratum is trees or mallees
Shrubland	Dominant stratum is shrubs; shrub referring to a perennial, woody, multi-stemmed plant of variable height (usually between 0.5 and 5 m tall), with branches arising from below or near ground level
Scrub	Dominant stratum is collectively composed of stunted trees and shrubs of variable height (usually greater than 0.5 m and less than 5 m tall), where plants generally have a distinguishable single stem or trunk
Heathland	Dominant stratum is perennial low shrubs (usually less than 2 m tall), commonly with ericoid leaves. Often from the Ericaceae, Fabaceae, Myrtaceae and Proteaceae families
Grassland	Dominant stratum is grasses. Subdivided into: hummock grasses, which consist of coarse xeromorphic grass with a mound-like form often dead in the middle (*Triodia* spp.); or tussock grasses, which form discrete but open tussocks usually with distinct individual shoots
Herbland	Dominant stratum is herbaceous or slightly woody annual herbs and weakly perennial low shrubs
Grove or stand	Dominant stratum is trees or tall shrubs confined to small areas
Thicket	Dominant stratum is collectively composed of stunted trees and/or tall scrub (usually greater than 2 m tall), where projected foliar cover is typically greater than or equal to 30%
Emergent	The tallest plants in some formations that are so sparse they do not form the dominant or most significant layer

Note: Vegetation formations were based on Specht (1970); Muir (1977); Hnatiuk et al. (2009); and NVIS (2017). Where a habitat type is described as a 'woodland or shrubland' the dominant stratum for locations supporting this habitat may occur as either trees or shrubs, respectively.

Cover classes

Cover classes assist with describing the horizontal distribution of vegetation. To be consistent with previous WA rangeland surveys, cover values were estimated using projected foliar cover (PFC). PFC is the percentage of the site occupied by the vertical projection of foliage only. It is measured by line interception methods which have been recorded as a reference set of calibrated photographic guides showing various types of vegetation formations. The PFC classes used are based on Curry et al. (1983) and are shown in Table 2.2 (Methods chapter).

Dominant and common plant species

Dominant species were those recorded as dominant in a stratum at a quarter or more of the inventory sites. Common species are subordinate and were those recorded as often abundant in density but rarely dominant at a quarter or more sampling sites. Where less than 8 inventory sites were sampled for a vegetation unit, dominant and common species were considered those present at a quarter or more sites. 'Other' species were recorded at a quarter of sampling sites and were sparse in abundance or were repeatedly mentioned in other floristic surveys but rarely, or not, encountered during this survey.

Species identification was based on collection material submitted to the Western Australian Herbarium and the list of plant species recorded in the survey area is in Volume 2, Appendix D. In some instances when habitat types could be matched, with reasonable confidence against other published vegetation communities, plant list information was validated against and complemented by previous floristic surveys in the region – Beard (1975, 1976, 1981); Hopkins and Robinson (1981); Newbey and Hnatiuk (1984, 1985, 1988); Keighery et al. (1992); Keighery et al. (1993); Newbey et al. (1995) – and further reviewed against floristic information contained in the WA Herbarium's database called Florabase for name currency and distribution (WAH 1998–). This was particularly useful for habitat types with limited sampling due to factors such as no accompanying traverse data (i.e. outside of pastoral leases), or seasonal influences and disturbance events which affected accessibility to locations or availability of suitable plant material to enable identification.

Taxonomic revision publications were also used because 2 prominent taxa identified in past floristic surveys have subsequently been recognised as belonging to complexes and have been renamed or further subdivided: *Eucalyptus flocktoniae* Complex (Nicolle and Conran 1999) and *Melaleuca uncinata* Complex (Craven et al. 2004). In the southern Goldfields survey, we identified *E. urna* where others may have identified *E. flocktoniae,* and *M. hamata* where others may have identified *M. uncinata*. The flora lists within this publication are therefore based on identified submitted collection material, supplemented with some previous floristic survey records, information within Florabase (WAH 1998–) at the time of publication and taxonomic revision publications (Nicolle and Conran 1999; Craven et al. 2004).

Taxonomic conventions

The plant taxonomy adopted in this survey was based on advice from the WA Herbarium. Species conservation status (DBCA 2019) was assigned according to the Threatened (declared rare) and priority flora list for Western Australia where threatened flora listings are reviewed annually by the Threatened Species Scientific Committee.

Threatened, Extinct and Specially Protected fauna or flora are species which have been adequately searched for and are deemed to be, in the wild, threatened, extinct or in need of special protection, and have been gazetted as such (DBCA 2019).

T Threatened flora

Threatened flora is that subset of 'Rare Flora' listed under schedules 1 to 3 of the *Wildlife Conservation (Rare Flora) Notice 2018*.

P Priority species

Possibly threatened species that do not meet survey criteria, or are otherwise data deficient, are added to the Priority flora lists under Priority One, Two or Three. These categories are ranked in order of priority for survey and evaluation of conservation status so that consideration can be given to their declaration as threatened flora.

Species that are adequately known, are rare but not threatened, or meet criteria for near threatened, or that have been recently removed from the threatened species or other specially protected flora lists for other than taxonomic reasons, are placed in Priority Four. These species require regular monitoring.

Assessment of priority codes is based on the Western Australian distribution of the species, unless the distribution in WA is part of a contiguous population extending into adjacent states, as defined by the known spread of locations (DBCA 2019).

P1 Priority One: Poorly known species

Species that are known from one or a few locations (generally 5 or less) which are potentially at risk. All occurrences are either: very small; or on lands not managed for conservation, for example, agricultural or pastoral lands, urban areas, road and rail reserves, gravel reserves and active mineral leases; or otherwise under threat of habitat destruction or degradation. Species may be included if they are comparatively well known from one or more locations but do not meet adequacy of survey requirements and appear to be under immediate threat from known threatening processes. Such species are in urgent need of further survey.

P2 Priority Two: Poorly known species

Species that are known from one or a few locations (generally 5 or less), some of which are on lands managed primarily for nature conservation. Species may be included if they are comparatively well known from one or more locations but do not meet adequacy of survey requirements and appear to be under threat from known threatening processes. Such species are in urgent need of further survey.

P3 Priority Three: Poorly known species

Species that are known from several locations, and the species does not appear to be under imminent threat, or from few but widespread locations with either large population size or significant remaining areas of apparently suitable habitat, much of it not under imminent threat. Species may be included if they are comparatively well known from several locations but do not meet adequacy of survey requirements and known threatening processes exist that could affect them. Such species are in need of further survey.

P4 Priority Four: Rare, Near Threatened and other species in need of monitoring

(a) Rare: species that are considered to have been adequately surveyed, or for which sufficient knowledge is available, and that are considered not currently threatened or in need of special protection but could be if present circumstances change. These species are usually represented on conservation lands.

(b) Near Threatened: species that are considered to have been adequately surveyed and that are close to qualifying for Vulnerable but are not listed as Conservation Dependent.

(c) Species that have been removed from the list of threatened species during the past 5 years for reasons other than taxonomy.

Assessment of ecological disturbances

Habitat types are described in terms of common or distinctive characteristics and internal variation. This reduces natural variation to a manageable number of ecological types within which there is strong similarity and facilitated assessment of rangeland condition. For grazing effects, the validity of condition assessments has been achieved by comparing the prominence of groups of plant species and soil surface condition at reference inventory sites (ungrazed or lightly grazed) to normally grazed sites. Influences on internal variation, caused by disturbances, are discussed in ecological terms rather than exclusively in terms of grazing effects on pastoral productivity, though it is common for most changes in productivity to be related to ecological changes.

Disturbances are considered in recognition of their widespread influence on the plants common to each habitat type. Disturbances are distinct events which may bring about variable growth rates and alter the survival among initial and late successional species within a specific location (Pickett et al. 1987; Collins et al. 1995). The scale of disturbance ranges from regional (e.g. climate change [Prober et al. 2012]) to localised (e.g. weed invasion). Ecological disturbance is discussed in terms of how disturbances, natural or anthropogenic (caused by humans), have affected the natural resources, which may have implications for future land management and nature conservation. The concepts may assist land managers to better understand and work with ecological processes operating throughout their leases.

In a regional survey, it can be difficult to establish rigorous scientific linkages between disturbances, such as grazing and ecological variation, both temporally and spatially (except where obvious, such as a recently burned area). Issues of scale and environmental variability across the region make sampling and interpreting of data problematic (Fox 1992; Landsberg et al. 2002). It is therefore important to appreciate many of the interpretations are based on the experience of the survey team and their ability to determine the cause and effects of disturbance. A substantial amount of data collected and analysed in adjacent surveys – the north-eastern Goldfields (Pringle et al. 1994), Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b) and the WA Nullarbor (Waddell et al. 2010) – provided information for many habitat types found in this survey. This information is summarised under relevant habitat descriptions to augment information collected during this survey.

Factors considered responsible for substantially influencing the ecology of Great Western Woodland habitat types include fire, wood harvesting and mining, weed encroachment, grazing and rabbit plagues, particularly in association with extended dry periods. In many instances, more than one disturbance was involved. Where a combination of factors has contributed to disturbance, it can be difficult to determine any single factor as the major cause, or to distinguish disturbance from natural variation. This was particularly relevant where there was little prior knowledge of the ecology of habitat types and their associated communities.

The ecological changes some habitat types have undergone have been so dramatic that the original species composition has been significantly altered. Altered associations occur where palatable, perennial species have been eliminated and replaced by unpalatable and/or annual species. For example, overgrazing by livestock and rabbit plagues, combined with drought or fire, has altered some chenopod shrublands. Habitat types in the southern Goldfields considered to have crossed thresholds and transitioned into altered states include: *Eucalyptus oleosa*, bindii woodland (EOBW), which is a degraded state of *Eucalyptus oleosa*, saltbush woodland (EOSW); and Annual herbland (ANNH), which is a severely degraded, post-transition state of Speargrass and wallaby grass open grassland (SWOG) or Atriplex low shrubland (ATLS). These particular habitat types are now considered to be in states of irreversible transition due to competition and diminished or lost seed banks (Westoby et al. 1989).

In some instances, a habitat type may have 2 forms: a ‘natural’ form and a ‘degraded’ form that resembles another habitat type. For example, Plain eucalypt, saltbush woodland (PESW) has a natural form, and a degraded form that resembles a Plain eucalypt, eremophila woodland (PEEW) when there is scrub encroachment by *Eremophila scoparia* (broom bush).

A Plain eucalypt, saltbush woodland in good condition in the Gumland land system

A degraded Plain eucalypt, saltbush woodland in the Gumland land system resembling a Plain eucalypt, eremophila woodland after scrub encroachment by *Eremophila scoparia* (broom bush)

Indicator terms for plant species with relevance to grazing

The indicator terms used to refer to plant species relevant to grazing are outlined in Table 6.4.

Table 6.4: Definition of indicator terms for plant species relevant to grazing

Term	Description
Decreaser	Highly palatable plants whose cover and density decrease in response to increased grazing pressure. In a grazing context, such plants may be referred to as 'desirables'
Intermediate	Moderately palatable plants, which under grazing may increase in abundance as they grow in niches vacated by decreasers, but because they are palatable, they eventually decrease as grazing pressure increases. Intermediate plants may dominate specific strata and be common in areas regenerating from severe degradation
Increaser	Generally unpalatable plants which increase in number and cover as decreaser species decrease with grazing pressure. They are commonly found in disturbed areas (e.g. water sources, burnt patches). In a grazing context, such plants may be referred to as 'undesirables'
No indicator value	These plants usually only decrease in number after natural disturbance events, such as fire or hail damage. They are usually not palatable; or only slightly palatable; or are out of reach of browsing animals. Abundance of these plants is not primarily related to grazing. They may be termed 'stability desirables' in recognition of their role in maintaining soil stability and ecosystem function

Plants considered to have a distinctive indicator value in response to grazing are referred to as key decreasers (KD) and key increasers (KI) and are denoted in stratum species lists in the habitat type descriptions below to support future rangeland assessments or monitoring. Information on palatability of flora to livestock and favoured forage species is largely based on previous WA rangeland survey technical bulletins and these specific publications: Mitchell and Wilcox (1994); Burnside et al. (1995); Fletcher (1995); Russell and Fletcher (2003); Addison (2012); Rangelands NRM (2015).

Habitat types in the survey area

Eighty-eight habitat types (numbered 1–88) split into 13 broader habitat type groups (denoted A–M) were identified in this survey (Table 6.5). Forty-nine of these habitat types are described for the first time.

In some instances subtypes have been recognised within the habitat types. Subtypes were used to record species- or landform-specific information in the field when there was a distinct variation from the main habitat type. Subtypes may be distinguished by the floristics of the most prominent stratum or where there is a difference between landforms despite the physiognomy and composition remaining similar. Some habitat types have been previously described in great detail because of their occurrence in the adjacent rangeland surveys (Pringle et al. 1994; Payne et al. 1998b; Waddell et al. 2010). Consequently, some of these habitat types were not sampled as intensively during this survey despite their frequency in the survey or in the traverse record.

In this section, habitat types are grouped and presented according to their typical position within a catena sequence. The habitat types listed first generally occur in the higher landscape positions (ranges, hills and granite domes), moving down through sandplains and plains, and concluding in lowland positions (lakes and swamps).

Table 6.5: Summary of the habitat type groups and their component habitat types

Habitat type number, code and name			Structural classification	
			NVIS (2017)	**Muir (1977)**
A	**Hill, ridge and breakaway plateau shrubland or woodland habitats**			
1	GHAS	Greenstone hill acacia shrubland	Open shrubland/ Closed shrubland	Scrub/Dense thicket
2	GHEW	Greenstone hill eucalypt woodland	Woodland/ Open forest	Low woodland A/ Low forest A
3	GMSW	Greenstone mallee, spinifex woodland	Mallee woodland/ Open mallee forest	Open tree mallee/ Tree mallee
4	ASST	Allocasuarina, spinifex scrub–thicket	Open shrubland	Low scrub A
4a	ASST–S	Subtype: Allocasuarina, spinifex scrub–thicket – sand sheet		
5	CRIW	Casuarina ridge woodland	Open woodland / Woodland	Open low woodland A/ Low woodland A
6	BXSW	Breakaway mixed shrubland or woodland	Open shrubland	Low scrub B/Scrub
7	LENW	Lateritic eucalypt, non-halophytic woodland	Woodland	Woodland
8	BFSS	Breakaway footslope shrubland	Open shrubland	Dwarf scrub D
9	GRDT	Granite dome thicket	Open shrubland/Shrubland	Scrub/Thicket
10	GRHW	Granite hill mixed woodland	Woodland	Low woodland B/ Low forest B
B	**Stony plain and low rise non-halophytic shrubland or woodland habitats**			
11	SGRS	Sandy granitic acacia shrubland	Sparse shrubland/ Open shrubland	Open low scrub A/ Low scrub A
12	GETT	Granitic pediment eucalypt, tall shrub thicket	Open shrubland/Shrubland	Scrub/Thicket
13*	GABS	Granitic acacia, *Borya* shrubland	Open rushland/ Closed rushland	Open mat plants/ Dense mat plants
14	SCJS	Stony close jam shrubland	Open shrubland/Shrubland	Scrub/Thicket
14a	JASP	Subtype: Jam shrubland over spinifex	Open shrubland/Shrubland	Scrub/Thicket
15	SCDS	Stony casuarina, dodonaea shrubland	Open shrubland	Low scrub A
16	GENW	Gravelly eucalypt, non-halophytic woodland	Woodland	Woodland
17	EBBG	Eucalypt blackbutt grove or stand	Woodland/Open forest	Woodland/Forest
18	LASC	Lateritic allocasuarina scrub	Shrubland	Thicket
18a	LASC–G	Subtype: Lateritic allocasuarina scrub – gravel	Shrubland	Thicket
18b	LASC–H	Subtype: Lateritic allocasuarina scrub – hill	Shrubland	Thicket

(continued)

Table 6.5 continued: Summary of the habitat type groups and their component habitat types

Habitat type number, code and name			Structural classification: NVIS (2017)	Structural classification: Muir (1977)
19	EENW	*Eucalyptus ebbanoensis, Neurachne annularis* woodland	Mallee woodland/ Open mallee forest	Open tree mallee/ Tree mallee
20*	IWWL	Inland wandoo woodland	Woodland	Low woodland A
21*	NAEW	*Neurachne annularis*, eucalypt woodland	Open mallee woodland	Very open tree mallee
22*	COTS	Cotton bush (*Ptilotus*) shrubland	Open shrubland/ Shrubland	Dwarf scrub D/Low heath D
23*	SDLS	Stony dodonaea low shrubland	Open shrubland	Dwarf scrub C
24*	RCEW	Ridge crest eucalypt woodland	Mallee woodland	Open tree mallee
25*	CXSS	Casuarina mixed scrub shrubland	Open woodland	Open low woodland A
C	**Stony plain and low rise chenopod shrubland or woodland habitats**			
26	BECW	Breakaway footslope eucalypt woodland with chenopod understorey	Woodland	Low woodland A
27	GEBW	Greenstone eucalypt, bluebush woodland	Open woodland/Woodland	Open low woodland A/ Low woodland A
28	GESW	Greenstone eucalypt, saltbush woodland	Woodland/Open forest	Low woodland A/ Low forest A
29	ERHW	*Eucalyptus ravida,* halophytic woodland	Woodland	Low woodland A
30	SCBS	Stony casuarina, bluebush shrubland	Open chenopod shrubland	Low scrub B
31	CPBS	Calcareous pearl bluebush shrubland	Open chenopod shrubland	Low scrub B
32	SBMS	Stony plain bluebush mixed shrubland	Sparse chenopod shrubland /Open chenopod shrubland	Open dwarf scrub D/ Dwarf scrub D
D	**Sandplain hummock grassland habitats**			
33	SASP	Sandplain spinifex hummock grassland	Open hummock grassland/ Hummock grassland	Hummock grass/ Mid-dense hummock grass
34	SAMA	Sandplain mallee, spinifex woodland	Mallee woodland/ Hummock grassland	Open tree mallee/ Mid-dense hummock grass
35	MHGW	Mallee, hummock grass (spinifex) woodland	Mallee woodland/ Hummock grassland	Open tree mallee/ Mid-dense hummock grass
36*	SAMU	Sandplain mulga, spinifex hummock grassland	Open hummock grassland	Hummock grass
37*	SAGS	Sandplain spinifex grassland with marble gum	Open hummock grassland	Hummock grass

(continued)

Table 6.5 continued: Summary of the habitat type groups and their component habitat types

			Structural classification	
Habitat type number, code and name			**NVIS (2017)**	**Muir (1977)**
E	**Sandplain shrubland habitats**			
38	SACS	Sandplain acacia shrubland	Open shrubland/Shrubland	Scrub/Thicket
39	SAHE	Sandplain heathland	Open heathland/ Closed heathland	Dwarf scrub C/ Dense Low Heath C
40	SCMS	Sandplain close mixed shrubland	Open heathland/ Closed heathland	Low scrub A/ Dense Heath A
41	SAMH	Sand sheet mallee heath	Mallee shrubland	Shrub mallee
42	SCES	Sandplain crest eucalypt stand	Mallee woodland/ Open mallee forest	Open tree mallee/ Tree mallee
F	**Plains transitional to sandplain habitats**			
43	PEAW	Plain eucalypt (mallee), acacia woodland	Mallee woodland	Open tree mallee
44	PYAW	Plain York gum, acacia woodland	Mallee woodland/ Open mallee forest	Open tree mallee/ Tree mallee
45	PINH	Plain native pine, heathland	Open heathland/ Closed heathland	Dwarf scrub C/ Dense Low Heath C
46*	PINW	Plain native pine, acacia woodland	Woodland	Low woodland A
G	**Sheetwash hardpan plain shrubland or woodland habitats**			
47	HPMS	Hardpan plain mulga shrubland	Woodland/Open forest	Low woodland A/ Low forest A
48	HMCS	Hardpan plain mulga shrubland with scattered chenopods	Open shrubland	Low scrub A
49	DRAS	Drainage tract acacia shrubland	Open shrubland/Shrubland	Scrub/Thicket
50	DACS	Drainage tract acacia shrubland or woodland with chenopod understorey	Open shrubland/Shrubland	Scrub/Thicket
H	**Sheetwash plain woodland habitats**			
51	CEWS	Colluvial slope eucalypt woodland over non-halophytic shrubland	Woodland	Low woodland A/ Woodland
52	PEBW	Plain eucalypt, bluebush woodland	Woodland	Woodland
53	EFBW	Eucalypt, false bluebush woodland	Woodland	Low woodland A
54	ETTW	Eucalypt, teatree woodland	Woodland/Open forest	Low woodland A/ Low forest A
55	DEMF	Dense eucalypt, melaleuca forest	Open forest/Closed forest	Low forest A – Forest/ Dense forest
55a	DBMF	Subtype: Dundas blackbutt, melaleuca forest	Open forest/Closed forest	Forest/Dense forest

(continued)

Table 6.5 continued: Summary of the habitat type groups and their component habitat types

Habitat type number, code and name			Structural classification	
			NVIS (2017)	Muir (1977)
56*	EOSW	*Eucalyptus oleosa*, saltbush woodland	Woodland/Open forest	Low woodland A/ Low forest A
57*	EOBW	*Eucalyptus oleosa*, bindii woodland	Woodland/Open forest	Low woodland A/ Low forest A
I	**Depositional plain woodland over shrubland habitats**			
58	PESW	Plain eucalypt, saltbush woodland	Woodland	Low woodland A/Woodland
59	PEEW	Plain eucalypt, eremophila woodland	Woodland	Low woodland A/Woodland
60	PEHW	Plain eucalypt, halophytic woodland	Woodland	Low woodland A/Woodland
61	DREW	Drainage tract eucalypt woodland	Woodland/Closed forest	Woodland/Dense forest
62	PPWL	Playa plain woodland	Woodland/Open forest	Low woodland A/ Low forest A
63	LSMX	Lakeside (sand sheet) mallee woodland with spinifex	Mallee woodland	Open tree mallee
64	LSES	Lakeside (sand sheet) eucalypt woodland with shrubs	Woodland/Open forest	Low woodland A/ Low forest A
64a	LSBS	Subtype: Lakeside (sand sheet) *Bossiaea* shrubland	Mallee woodland/ Open mallee forest	Low woodland A/ Low forest A
65*	LDCW	Lakeside dune *Callitris* woodland	Woodland	Low woodland B
66*	LDPH	Lakeside dune proteaceous heathland	Open heathland/Heathland	Scrub/Thicket
67*	LSCS	Lakeside sandy bank casuarina shrubland	Sparse shrubland	Open scrub
68*	EMMS	Eucalypt mallee, melaleuca shrubland	Mallee woodland/ Open mallee forest	Open tree mallee/ Tree mallee
J	**Depositional plain mixed halophyte shrubland habitats**			
69	SBLS	Sandy bank lake shrubland	Open shrubland	Scrub
70	PXHS	Plain mixed halophyte shrubland	Open chenopod shrubland/ Chenopod shrubland	Dwarf scrub C/Low heath C
71	SAMP	Samphire shrubland	Sparse samphire shrubland/ Samphire shrubland	Dwarf scrub D/Low heath C
72	BLSS	Bladder saltbush low shrubland	Open chenopod shrubland/ Chenopod shrubland	Dwarf scrub D/Low heath D
73	PSAS	Plain sago bush shrubland	Open chenopod shrubland	Dwarf scrub C

(continued)

Table 6.5 continued: Summary of the habitat type groups and their component habitat types

Habitat type number, code and name			Structural classification NVIS (2017)	Muir (1977)
74*	FRAN	Frankenia low shrubland	Open shrubland/Shrubland	Open dwarf scrub D/ Dwarf scrub D
75*	SWCS	Sugarwood mixed chenopod shrubland	Open shrubland	Low scrub B
76*	ATLS	Atriplex low shrubland	Open chenopod shrubland	Dwarf scrub D
K	**Depositional plain grassland habitats**			
77	SWOG	Speargrass and wallaby grass open grassland	Sparse tussock grassland/ Open tussock grassland	Very open low grass/ Open low grass
78	ANNH	Annual herbland	Sparse forbland/ Open forbland	Very open herbs/ Open herbs
L	**Calcrete or kopi associated woodland or shrubland habitats**			
79	KOPI	Kopi dune woodland	Open woodland/Woodland	Open low woodland A/ Low woodland A
80	CCAS	Calcareous casuarina, acacia shrubland or woodland	Woodland	Low woodland A
81*	CCCW	Calcareous casuarina, *Cratystylis* woodland	Woodland	Low woodland A
M	**Drainage focus habitats**			
82	DFEW	Drainage focus eucalypt woodland	Woodland	Low woodland A
82a	DFEW–S	Subtype: Drainage focus *E. salubris* woodland	Woodland	Low woodland A
82b	DFEW–U	Subtype: Drainage focus *E. urna* woodland	Woodland	Low woodland A
82c	DFEW–D	Subtype: Drainage focus *E. diptera* woodland	Woodland	Low woodland A
82d	DFEW–T	Subtype: Drainage focus *E. terebra* woodland	Woodland	Low woodland A
83	SWEW	Swamp eucalypt woodland	Woodland/Open forest	Low woodland A/ Low forest A
84	MESS	Melaleuca swamp shrubland	Shrubland	Thicket
85*	LISW	Lignum swamp	Open shrubland/Shrubland	Low scrub B/Heath B
86*	PXLS	Plain mixed low shrubland	Open shrubland/Shrubland	Dwarf scrub C/Low heath C
87*	SEDF	Sedgeland drainage focus	Open sedgeland/Sedgeland	Dwarf scrub C/Low heath C
88*	THKD	Thicket: dodonaea	Shrubland	Thicket

* Uncommon habitat type

Note: Structural definitions for this survey were based on the National Vegetation Information System (NVIS 2017). Structural definitions according to Muir's (1977) classification are provided to aid comparison with previous WA rangeland surveys.

A Hill, ridge and breakaways plateau shrubland or woodland habitats

These habitat types occur on hills, ridges and breakaways and are characterised by shallow soils exhibiting little or no profile development, with surfaces regularly having an abundant stony mantle. Vegetation coverage ranges from very scattered to closed and is often inversely related to the amount of outcrop present and influenced by gradient and soil depth. Vegetation varies from eucalypt or casuarina woodlands, acacia-dominated tall shrublands, mixed shrublands on ferruginous breakaway plateaus, thickets associated with drainage foci on granite domes, or stony, spinifex-dominated grasslands with scattered trees and shrubs. These habitat types have relatively low pastoral value and are generally not preferred by livestock; they are more likely to be damaged by goats than sheep and cattle. Mining is the major threat, particularly where greenstone mineral deposits, BIFs and different geological contacts occur.

1 Greenstone hill acacia shrubland (GHAS)

Sampling

15 inventory sites, 44 traverse points

General information

GHAS is described in the north-eastern Goldfields (Pringle et al. 1994) and Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b) surveys. It occurs on greenstone hills scattered throughout the survey area. Its southern Goldfields distribution is often subtly related to variations in relief, underlying geology and soil depth. GHAS is typical of the Eremaean Botanical Province (Beard 1990) and Murchison bioregion (Environment Australia 2000), and features in the central northern portion of the survey area.

GHAS tends to be associated with skeletal soils on the crests of hills and low rises underlain by mafic geology. It also occurs on some metasedimentary and ferruginous ridges and low rises in the east. Soils are usually very shallow (<30 cm) and stony with a loamy matrix, predominantly have a neutral pH and predominantly consist of mafic material (i.e. basalt and metabasalt). A stony mantle with abundant angular to subangular cobbles and stones is common.

Physiognomy and composition of vegetation

GHAS consists of scattered to closed (≥15% PFC) tall shrubland dominated by acacias, most commonly *Acacia quadrimarginea* (granite wattle), occasionally with a co-dominant mid or low shrub stratum. Trees and perennial grasses are usually a minor component if present.

Acacia quadrimarginea (granite wattle) tall shrubland on a hillslope in the Graves land system

The dominant and common species by strata:

Trees:	Dominant – rarely present as a recognisable stratum; *Acacia aneura* (in the north) and *Casuarina pauper* may be present
Mallees:	Dominant – rarely present as a recognisable stratum; *Eucalyptus griffithsii* may be present Others – *Eucalyptus ewartiana*, *E. oleosa* subsp. *oleosa*
Tall shrubs:	Dominant – *Acacia quadrimarginea*; occasionally *A. acuminata*, *A. aneura* (in the north), *A. burkittii* or *Allocasuarina* spp. Common – *Acacia tetragonophylla*, *Allocasuarina eriochlamys* subsp. *eriochlamys*, *Santalum spicatum* Others – *Allocasuarina huegeliana, Eremophila alternifolia*, *E. oppositifolia*, *Grevillea nematophylla* subsp. *nematophylla*
Mid shrubs:	Dominant – variable; *Acacia* spp., *Dodonaea* spp. and *Senna* spp. Common – *Acacia quadrimarginea*, *Dodonaea lobulata* (KI), *D. microzyga* var. *acrolobata*, *Eremophila clarkei*, *Scaevola spinescens*, *Senna artemisioides* subsp. *filifolia* (KI) Others – *Philotheca brucei*, *Pomaderris forrestiana*, *Senna artemisioides* subsp. *sturtii*, *Sida calyxhymenia* (KD), *Thryptomene* spp.
Low shrubs:	Dominant – often *Ptilotus obovatus* Common – *Prostanthera althoferi* subsp. *althoferi*, *Scaevola spinescens*, *Solanum lasiophyllum* Others – *Eremophila glabra* (KD), *Westringia rigida*
Perennial grasses:	Dominant – rarely present as a recognisable stratum Common – *Austrostipa elegantissima*, *A. scabra*
Other plant forms:	Occasional – *Cheilanthes lasiophylla* (fern), *Leichhardtia australis* (climber)

Priority flora

This habitat is known to support *Cyathostemon divaricatus* (Priority 1) in the greenstone hills near Kambalda.

Ecological disturbance

GHAS is not preferred for livestock because there is generally more palatable forage downslope. In good condition, there is often a mix of palatable species such as *Eremophila glabra* (tar bush), *Ptilotus obovatus* (cotton bush), *Scaevola spinescens* (currant bush) and *Sida calyxhymenia* (tall sida). In overgrazed situations, *Dodonaea lobulata* (bead hopbush) and *Senna artemisioides* subsp. *filifolia* (desert cassia) are more likely to be abundant. The absence of *P. obovatus* does not necessarily indicate poor condition because its abundance and occurrence are significantly influenced by seasonal conditions, and it is naturally spatially variable. GHAS is not generally susceptible to erosion unless the protective stone mantle is disturbed, which most often occurs with the construction of exploration tracks and drill pads.

Gradational associations

GHAS occurs throughout the survey area but becomes less common in the south as the dominance of acacias is replaced by eucalypts and casuarinas. Where eucalypts dominate the tree stratum, GHAS is replaced by either Greenstone hill eucalypt woodland (GHEW, #2) or Greenstone mallee, spinifex woodland (GMSW, #3). GHAS also tends to transition into these eucalypt associations as soils deepen on slopes adjacent to crests, and in response to changes in the underlying geology from mafic or metasedimentary to ultramafic material.

Where casuarinas dominate, GHAS is replaced by Casuarina ridge woodland (CRIW, #5), particularly on metasedimentary outcrop, or Lateritic allocasuarina scrub (LASC, #18), where greenstones abut ferruginous duricrusts.

GHAS typically transitions downslope into Stony casuarina, dodonaea shrubland (SCDS, #15) or Gravelly eucalypt, non-halophytic woodland (GENW, #16) as the tall shrub stratum becomes sparser and more clearly dominated by casuarinas or eucalypts, respectively, and where geology is associated with metabasalt or metasedimentary outcrop. GHAS may transition into Stony close jam shrubland (SCJS, #14) where *Acacia acuminata* (jam) dominates. Where the underlying footslopes are associated with ultramafic deposits, GHAS often transitions into Greenstone eucalypt, saltbush woodland (GESW, #28).

Land systems

GHAS is a major habitat type in the Graves, Hampton, Jaurdi and Quartzitehill land systems and minor habitat type in the Coolgardie, Greenmount, Kurrawang, Lawrence, Moriarty and Zed land systems.

2 Greenstone hill eucalypt woodland (GHEW)

Sampling

17 inventory sites, 87 traverse points

General information

GHEW is described for the first time. It occurs on greenstone hills and ridges. It occupies a similar part of the landscape to Greenstone hill acacia shrubland (GHAS, #1) though typically with denser, more structurally complex vegetation including trees, most noticeably eucalypts as they replace acacias as the dominant upper stratum. GHEW represents the mixed dry woodlands of the South-western Interzone (Beard 1990) and the Coolgardie and Mallee bioregions (Environment Australia 2000) which are common in the southern Goldfields, while GHAS is more typical of the Eremaean Botanical Province and Murchison bioregion, and features more often in the central northern portion of the survey. GHEW includes eucalypt communities described in Greenstone hill non-halophytic eucalypt woodland (GNEW) in the north-eastern Goldfields (Pringle et al. 1994) and Kambalda (Payne et al. 1998a) surveys.

GHEW usually occurs on very shallow (<30 cm), calcareous and loamy, stony soils of mafic or ultramafic origin, regularly with a stony mantle. Outcrop is often present and typically consists of basalt or metamorphosed rocks (greenstones) and occasionally BIF. The dominance of calcium carbonate within soil profiles is very common. Lower slopes with more gentle gradients aid colluvial accumulation and development of deeper soils. In these situations, Calcareous shallow loam or Calcareous loamy earth soils replace the stony soils.

Physiognomy and composition of vegetation

GHEW occurs as a scattered to closed (≥15% PFC) woodland, distinguished by the presence of eucalypts in the tree stratum. The understorey predominantly consists of non-halophytic shrubs, except for *Atriplex* spp. that may be locally common. The low and mid shrub strata are variably developed. Typically, the tree stratum dominates a low woodland with up to 30% PFC, though GHEW may also occur as a moderately close tall shrubland or scrub (≤25% PFC) with very scattered low trees (5–10% PFC), and scattered mid and low shrubs (10–20% PFC). Infrequent perennial grasses usually grow among shrubs.

The variability within the GHEW habitat type reflects the complex relationship between underlying geology, soil depth and topography. Eucalypts such as *E. griffithsii* (Griffith's grey gum) or *E. lesouefii* (Goldfields blackbutt) are regularly present, if not dominating the tree stratum on the greenstone hills supporting GHEW. However, depending on substrate and species distribution, in specific locations GHEW supports distinctive eucalypt associations with localised variations in the dominant trees. For example, eucalypt species such as *E. celastroides* (mirret) or *E. stricklandii* (Strickland's gum) occur on greenstones with ferruginous mantles; and *E. torquata* (coral gum) is often associated with ultramafic rocks. In these specific locations, while often not dominant in terms of cover, as open low woodlands, these species are usually the most common eucalypts over a locally variable shrub understorey.

The dominant and common species by strata:

Trees and mallees:	Dominant – mainly *Eucalyptus griffithsii*, *E. lesouefii*; occasionally *E. celastroides*, *E. celastroides* subsp. *celastroides*, *E. stricklandii*, *E. torquata*
	Others – *Casuarina pauper*, *Eucalyptus campaspe** (mid to lower slopes), *E. clelandiorum**, *E. salmonophloia* (lower footslopes)
Tall shrubs:	Dominant – *Acacia tetragonophylla*, *Alyxia buxifolia*
	Common – *Eremophila alternifolia*, *E. interstans* subsp. *interstans*, *E. oppositifolia*, *Exocarpos aphyllus*, *Santalum acuminatum*, *S. spicatum*
	Others – *Acacia acuminata*, *A. quadrimarginea*, *Allocasuarina acutivalvis* subsp. *acutivalvis*, *Grevillea nematophylla* subsp. *nematophylla*, *Melaleuca sheathiana*
Mid shrubs:	Dominant – variable; *Dodonaea* spp., *Eremophila* spp. and *Senna* spp.
	Common – *Atriplex nummularia* subsp. *spathulata*, *Dodonaea lobulata* (KI), *D. microzyga* var. *acrolobata*, *D. stenozyga*, *Eremophila glabra* (KD), *E. scoparia*, *Scaevola spinescens* (KD), *Senna artemisioides* subsp. *filifolia* (KI), *Trymalium myrtillus* subsp. *myrtillus*
	Others – *Eremophila georgei*, *Ricinocarpos stylosus**, *Senna cardiosperma**
Low shrubs:	Dominant – variable; *Acacia erinacea*, *Olearia muelleri*, *Ptilotus obovatus*, *Scaevola spinescens* (KD)
	Common – *Atriplex vesicaria* (KD), *Dodonaea microzyga* var. *acrolobata*, *Eremophila parvifolia* subsp. *auricampa* (KD), *Hybanthus floribundus* subsp. *curvifolius**, *Prostanthera grylloana*, *Solanum* spp., *Westringia rigida*
	Others – *Grevillea acuaria**, *Halgania andromedifolia*
Perennial grasses:	Dominant – rarely present as a recognisable stratum
	Common – *Austrostipa elegantissima* (KD), *A. nitida**, *A. platychaeta* (KD)
Other plant forms:	Common – *Sclerolaena diacantha* (perennial herb)
	Occasional – *Leichhardtia australis* (climber)

* Also known from Beard (1990); Cole (1992); Meissner and Coppin (2013)

Priority flora

Grevillea phillipsiana (Priority 1) was recorded at one site. This habitat is known to contain some species found near BIFs such as *Grevillea georgeana* (Priority 3).

Ecological disturbance

There is little evidence to suggest that grazing by livestock threatens GHEW, though uncontrolled goat populations may reduce the diversity and density of some palatable plant species. There is generally more palatable forage downslope. Palatable species, such as *Atriplex vesicaria* (bladder saltbush), *Austrostipa elegantissima* (feather speargrass), *A. platychaeta*, *Eremophila glabra* (tar bush), *E. parvifolia* subsp. *auricampa*, *Ptilotus obovatus* (cotton bush) and *Scaevola spinescens* (currant bush), may be reduced through overgrazing, with *Dodonaea lobulata* (bead hopbush) and *Senna artemisioides* subsp. *filifolia* (desert cassia) possibly increasing in density in response to reduced resource competition. *P. obovatus* abundance is influenced by seasonal conditions and its occurrence is spatially variable, so absence does not always indicate poor condition. Stone mantles usually provide effective protection against erosion unless there is disturbance, such as during exploration activity.

Gradational associations

GHEW occurs throughout the survey but is less common in the north. It is replaced by Greenstone hill acacia shrubland (GHAS, #1) where acacias begin to dominate greenstone hills. Where greenstones abut BIFs and ferruginous duricrusts and Casuarinaceae dominate, GHEW is replaced by Allocasuarina, spinifex scrub–thicket (ASST, #4) or Lateritic allocasuarina scrub (LASC, #18).

On hillslopes and footslopes, GHEW frequently transitions downslope into: Gravelly eucalypt, non-halophytic woodland (GENW, #16), as the tree stratum becomes more open and the mid and low shrub strata become denser; Greenstone eucalypt, saltbush woodland (GESW, #28) where *Atriplex* spp. increase in prominence in the understorey; or Greenstone mallee, spinifex woodland (GMSW, #3) where spinifex becomes the dominant understorey plant.

Land systems

GHEW is a major habitat type in the Graves, Moriarty and Noganyer land systems and a minor habitat type in the Coolgardie, Dryandra, Hampton and Jaurdi land systems.

Eucalypt woodland co-dominated by *Eucalyptus lesouefii* (Goldfields blackbutt) and *E. torquata* (coral gum) over mixed shrubs on a hillslope in the Jaurdi land system

3 Greenstone mallee, spinifex woodland (GMSW)

Sampling

14 inventory sites, 56 traverse points

General information

GMSW is described for the first time. It occupies a similar part of the landscape to Greenstone hill eucalypt woodland (GHEW, #2), occurring on greenstone ranges, hills and low rises, though the understorey is structurally less complex because of the predominance of *Triodia scariosa* (spinifex). GMSW occurs on soils with greater development and often on a more deeply weathered mantle than GHEW, with calcium carbonate concentrating in the upper profile. Soils are most often very shallow (<30 cm), either with calcrete hardpans or rock substrate (most commonly greenstone and metabasalt, but also schist and weathered granite) limiting the soil depth. Very shallow soil over calcrete, Calcareous stony soil and Calcareous shallow loam or sandy earth or ironstone gravel soils are most common, with occasional non-calcareous Stony soil and Very shallow soil. An abundant stony mantle composed of mafic rocks of similar chemical composition but varied texture occurs regularly, with occasional outcrop.

Physiognomy and composition of vegetation

GMSW consists of scattered to close (15–50% PFC) mallee woodland, characterised by spinifex understorey. Tall shrubs may occur as close stands or groves. The mid and low shrub strata are variably developed, but typically scattered. *Eucalyptus griffithsii* (Griffith's grey gum) and *E. lesouefii* (Goldfields blackbutt) are relatively common. Other eucalypts also growing on shallow soils over greenstones may dominate specific locations because of their distribution within the survey area: *E. ebbanoensis* (sandplain mallee) in the north-west, *E. effusa* subsp. *effusa* in the south-east (east of Fraser Range), and *E. torquata* (coral gum) which is common to greenstones in central areas. Variation in overall coverage is usually due to varying abundance within the hummock grass stratum.

The dominant and common species by strata:

Trees:	Dominant – mainly *Eucalyptus lesouefii*; occasionally *E. torquata*
Mallees:	Dominant – mainly *Eucalyptus griffithsii*; occasionally *E. ebbanoensis* (in the north-west), *E. effusa* subsp. *effusa* (east of Fraser Range), *E. oleosa* subsp. *oleosa*
Tall shrubs:	Dominant – variable Common – *Acacia hemiteles*, *Allocasuarina helmsii*, *A. huegeliana*, *Alyxia buxifolia*, *Exocarpos aphyllus*, *Melaleuca eleuterostachya* Others – *Acacia tetragonophylla*, *Eremophila interstans* subsp. *interstans*, *Santalum acuminatum*, *S. spicatum*
Mid shrubs:	Dominant – rarely present as a recognisable stratum Common – *Dodonaea lobulata*, *D. stenozyga*, *Eremophila scoparia*, *Senna artemisioides* subsp. *filifolia* Others – *Calothamnus gilesii*, *Eremophila parvifolia* subsp. *auricampa* (KD), *Thryptomene australis**
Low shrubs:	Dominant – rarely present as a recognisable stratum Common – *Acacia erinacea*, *A. pachypoda*, *Dodonaea adenophora*, *Scaevola spinescens* (KD), *Westringia rigida*

	Others – *Cryptandra* spp., *Hybanthus floribundus* subsp. *curvifolius*, *Olearia muelleri*
Perennial grasses:	Dominant – *Triodia scariosa*
	Occasional – *Austrostipa elegantissima*
Other plant forms:	Occasional – *Dianella revoluta* (perennial herb), *Gahnia* spp. (sedge)

* Also known from Keighery et al. (1993)

Priority flora

Acacia kerryana (Priority 2) was recorded at one site. This habitat type is known to support *Eucalyptus platydisca* (Jimberlana mallee; Threatened) on Jimberlana Hill east of Norseman.

Ecological disturbance

GMSW is largely unaffected by grazing and has very low pastoral value. The hummock grasses and most shrubs are unattractive to livestock, and it often occurs on areas with poor accessibility for livestock, such as the crests and upper slopes of ranges and hills. Where a stony mantle is extensive, the susceptibility to erosion is low unless there is disturbance such as exploration tracks and drill pads. In areas with calcareous shallow loams and where protective stone mantles are absent, erosion may occur and cause a reduction in spinifex coverage, particularly after fire.

Gradational associations

On greenstone ranges, hills and low rises, GMSW transitions into Greenstone hill eucalypt woodland (GHEW, #2) as spinifex dominance is replaced by shrubs. On footslopes, GMSW frequently transitions downslope into Gravelly eucalypt, non-halophytic woodland (GENW, #16) as the tree stratum opens and the mid and low shrub strata become denser. Where the tree or tall shrub strata begin to change from mallee-dominated to Casuarinaceae-dominated, GMSW is replaced by Allocasuarina, spinifex scrub–thicket (ASST, #4). Elsewhere, owing to its association with mafic outcrop, GMSW communities may be quite different from the surrounding plains, and it is a distinctive habitat type with clearly defined boundaries.

Land systems

GMSW is a major habitat type in the Gnamma, Hampton, Jimberlana and Yandamurrina land systems and a minor habitat type in the Moriarty land system.

Eucalyptus lesouefii (Goldfields blackbutt) and *E. oleosa* subsp. *oleosa* (giant mallee) over *Triodia scariosa* (spinifex) on a basalt hillslope in the Hampton land system

4 Allocasuarina, spinifex scrub–thicket (ASST)

Subtype: Allocasuarina, spinifex scrub–thicket – sand sheet (ASST–S)

Sampling

ASST: 6 inventory sites, 2 traverse points

ASST–S: 1 inventory site, 5 traverse points

General information

ASST is described for the first time. It is an uncommon habitat, which typically occurs on ranges, hills and low rises associated with greenstones, though variations occur on ferruginous landforms. ASST typically occurs on very shallow soils with a neutral to acid pH, underlain by rock. An extensive stony mantle consisting of mafic and ferruginous, subangular, coarse gravels and stones is a regular occurrence, with outcrop also common.

A subtype of ASST is Allocasuarina, spinifex scrub–thicket – sand sheet (ASST–S). While the physiognomy and composition are relatively similar ASST–S occurs on shallow sand sheets underlain variably by cemented ironstone gravel, silcrete hardpans or granitic pediment. ASST was treated as the major habitat type and ASST–S was used as a component to provide landform-specific information in the field, particularly when traversing.

Physiognomy and composition of vegetation

ASST typically consist as scattered (>10–20% PFC) *Allocasuarina*-dominated tall scrub over an understorey of *Triodia* spp. (spinifex) hummock grasses of variable abundance. Occasionally, stands of allocasuarina may occur together forming moderately close to close (25–50% PFC) thickets. *A. helmsii* frequently dominates the tall shrub stratum, though it may be replaced by other species of *Allocasuarina* in some locations. When present, the tree stratum is very scattered to scattered (5–15% PFC). The mid and low shrub strata are often sparse or absent.

The dominant and common species by strata:

Trees:	Dominant – rarely present other than as emergents; occasionally *Eucalyptus torquata*
Mallees:	Dominant – rarely present other than as emergents; occasionally *Eucalyptus concinna*, *E. griffithsii*
Tall shrubs:	Dominant – *Allocasuarina helmsii*; occasionally *A. acutivalvis* subsp. *acutivalvis*, *A. eriochlamys* subsp. *grossa*
	Common – *Acacia burkittii*, *A. quadrimarginea*, *Alyxia buxifolia*
	Other – *Santalum acuminatum*
Mid shrubs:	Dominant – juvenile *Allocasuarina* spp., otherwise rarely present as a recognisable stratum
	Common – *Allocasuarina helmsii*
	Others – *Dodonaea lobulata*, *D. stenozyga*
Low shrubs:	Dominant – rarely present as a recognisable stratum
	Common – *Cryptandra aridicola*, *Scaevola spinescens* (KD)
Perennial grasses:	Dominant – *Triodia scariosa*, occasionally *T. irritans*

Priority flora

Acacia dorsenna (Priority 1) and *Eucalyptus pterocarpa* (Priority 4) were recorded at one site each.

Ecological disturbance

ASST has very low pastoral value because most shrubs and hummock grasses are unattractive to livestock, though on occasion excessive grazing by goats had significantly degraded stands of *Allocasuarina helmsii* associated with ASST–S. Stony mantles reduce the susceptibility to erosion unless there is disturbance such as occurs with exploration activity.

Gradational associations

ASST is a distinctive habitat type with clearly defined boundaries, except where the tree or tall shrub dominance changes from Casuarinaceae to mallees and ASST is replaced by Greenstone mallee, spinifex woodland (GMSW, #3). Where BIFs and ferruginous duricrusts abut greenstones, and where spinifex decreases in abundance, ASST is replaced by Lateritic allocasuarina scrub (LASC, #18), or Greenstone hill eucalypt woodland (GHEW, #2) where eucalypts dominate.

Land systems

ASST is a major habitat type in the Hampton land system. Elsewhere, it is an uncommon habitat type infrequently associated with ferruginous landforms in land systems such as Bannar, Bevon, Jaurdi and Widgiemooltha.

ASST–S is a minor habitat type in the Kirgella and Sedgeman land systems.

Crest of a low ridge on a dolerite dyke, supporting scattered *Allocasuarina helmsii* tall shrubs over *Triodia scariosa* (spinifex) in the Widgiemooltha land system

5 Casuarina ridge woodland (CRIW)

Sampling

7 inventory sites, 18 traverse points

General information

CRIW is described for the first time. It is common to many of the metasedimentary ridges and low rises scattered throughout the survey area. Ridges are typically composed of in situ, angular, metasedimentary or siliceous rock types. Bare rock is common and if soil is present, it is Very shallow soil with a loamy matrix and a neutral or acidic pH.

Physiognomy and composition of vegetation

CRIW commonly consists of very scattered to scattered (5–20% PFC) stands of *Casuarina pauper* (black oak) trees. The tall, mid and low shrub strata are variably developed.

The dominant and common species by strata:

Trees:	Dominant – *Casuarina pauper* Common – *Acacia aneura*
Tall shrubs:	Dominant – variable; often *Eremophila* spp. Common – *Acacia tetragonophylla*, *Alyxia buxifolia*, *Eremophila alternifolia*, *E. oldfieldii* subsp. *angustifolia*, *E. oppositifolia* Others – *Acacia burkittii*, *Exocarpos aphyllus*, *Psydrax suaveolens*, *Santalum spicatum*
Mid shrubs:	Dominant – variable Common – *Dodonaea lobulata* (KI), *Eremophila glabra* (KD), *Philotheca brucei*, *Prostanthera althoferi* subsp. *althoferi*, *Scaevola spinescens* (KD), *Senna artemisioides*, *S. artemisioides* subsp. *filifolia* (KI) Others – *Atriplex nummularia* subsp. *spathulata*, *Sida calyxhymenia* (KD)
Low shrubs:	Dominant – variable Common – *Acacia erinacea*, *Atriplex vesicaria* (KD), *Enchylaena tomentosa* (KD), *Lycium australe*, *Maireana pyramidata*, *M. sedifolia*, *Olearia muelleri*, *Ptilotus obovatus*, *Scaevola spinescens* (KD)
Other plant forms:	Common – *Cheilanthes sieberi* (fern), *Leichhardtia australis* (climber), *Sclerolaena diacantha* (perennial herb)

Ecological disturbance

Not much is known. Presumably, palatable understorey species could be removed under excessive grazing pressure. These include *Atriplex vesicaria* (bladder saltbush), *Enchylaena tomentosa* (ruby saltbush), *Eremophila glabra* (tar bush), *Ptilotus obovatus* (cotton bush), *Sida calyxhymenia* (tall sida) and *Scaevola spinescens* (currant bush). It is difficult to confidently assess grazing impacts because of the natural variability in this habitat's flora. Usually there is more palatable forage downslope on the surrounding plains. Bare rock and dense stony mantles provide effective protection against erosion.

Gradational associations

CRIW typically occurs on metasedimentary ridges and transitions downslope into Stony casuarina, bluebush shrubland (SCBS, #30) as *Maireana sedifolia* (pearl bluebush) increases in abundance. Where greenstones, ferruginous duricrusts and BIFs abut other metasedimentary rock types, CRIW often transitions into Stony casuarina, dodonaea shrubland (SCDS, #15).

Land systems

CRIW is a major habitat type in the Lawrence land system and minor habitat type in the Kanowna, Kurrawang, Moriarty and Zed land systems. Variations may also occur in the Dryandra land system.

Casuarina ridge woodland associated with a low, linear quartz ridge

6 Breakaway mixed shrubland or woodland (BXSW)

Sampling

14 inventory sites, 8 traverse points and numerous ad hoc searches for unusual flora

General information

BXSW is similar to the Breakaway mixed shrubland (BRXS) habitat described in the north-eastern Goldfields (Pringle et al. 1994) and the Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b) surveys. However, it is described as a different habitat in this survey because of the occasional eucalypts in the upper stratum. BXSW is most common on stony plateau surfaces between sandplain and breakaway scarps in deeply weathered landscapes associated with granite and shear zones. It also occurs as narrow bands of exposed, stripped surfaces in extensive areas of sandplain, such as in the Joseph and Kirgella land systems. Indurated surfaces of ferruginous sedimentary rocks are also common on the western edge of lake systems in the Kambalda and Dundas zones.

Breakaway plateaus form when an indurated layer or cap develops over less resistant regolith and decomposing rock. In BXSW, the indurated layer most commonly forms by iron or silica cementation of soil or regolith. Breakaway edges collapse when the soft, weathered rock of the scarp face erodes under the resistant cap or, when associated with lake systems, swash processes undermine less resistant rocks. Plants are found growing in the nutrient-depleted Very shallow soil over ferruginous duricrust and Very shallow stony soils derived from decomposing granite, silcrete or ferruginised duricrust. Occasionally, soils are deeper and form Shallow loamy gravel and strongly acidic duplex soils on colluvial and in situ slopes of breakaways. Where eucalypts and casuarinas become present in sufficient density, soils may show calcareous overprinting and form Calcareous gravelly shallow loam and Calcareous stony soils. Forms of BXSW are also found remote from sandplains on some hill crests and low rises where the parent rock has become ferruginous and indurated.

Physiognomy and composition of vegetation

BXSW usually consists of scattered low shrublands (>10–20% PFC), with occasional patches of moderately close (>20–30% PFC) mid to tall scrub. The tree stratum is generally infrequent and very scattered, though *Eucalyptus lesouefii* (Goldfields blackbutt) or *E. stricklandii* (Strickland's gum) are often present, with *E. capillosa* (inland wandoo) more common in the west of the survey area. *Casuarina pauper* (black oak) is also often present. The composition of breakaway communities is floristically variable.

Breakaway mixed shrubland consisting of *Melaleuca hamata* and *Leucopogon validus* with very scattered *Eucalyptus capillosa* (inland wandoo) on an ironstone gravelly scree slope below a ferruginous duricrust

As well as listing species which were often recorded, the list below includes some species which were recorded infrequently during this survey but featured regularly on breakaway landforms in the WA Museum biological survey records (Newbey and Hnatiuk 1984, 1985, 1988; Newbey et al. 1995).

The dominant and common species by strata:

Trees and mallees:	Dominant – rarely present as a recognisable stratum; occasionally *Eucalyptus capillosa* (in the west), *E. lesouefii*, *E. stricklandii*
	Common – *Casuarina pauper*, *Eucalyptus lesouefii* (when other species are dominant)
	Others – *Eucalyptus celastroides* subsp. *celastroides* (mallee), *E. cylindrocarpa* (mallee), *E. griffithsii* (mallee)
Tall shrubs:	Dominant – variable; often *Acacia* spp.
	Common – *Acacia tetragonophylla*, *Alyxia buxifolia*, *Eremophila oppositifolia*, *Exocarpos aphyllus*, *Grevillea nematophylla* subsp. *nematophylla*, *Melaleuca hamata*, *Santalum acuminatum*, *S. spicatum*
	Others – *Acacia acuminata*, *A. quadrimarginea*, *Eremophila alternifolia*
Mid shrubs:	Dominant – variable; often *Dodonaea* spp.
	Common – *Acacia hemiteles*, *Dodonaea lobulata*, *D. rigida* (KD), *D. stenozyga*, *Eremophila glabra* (KD)
	Others – *Eremophila clarkei*, *Philotheca brucei*, *Sida calyxhymenia* (KD), *Trymalium myrtillus* subsp. *myrtillus*
Low shrubs:	Dominant – variable
	Common – *Acacia erinacea*, *Cryptandra aridicola*, *Eremophila parvifolia* subsp. *auricampa* (KD), *Grevillea acuaria*, *Olearia muelleri*, *Ptilotus obovatus*, *Prostanthera* spp., *Scaevola spinescens*, *Westringia rigida*
	Others – *Eremophila latrobei* (KD), *E. pustulata*, *Leucopogon* spp., *Ptilotus helichrysoides*
Other plant forms:	Occasional – *Cheilanthes* spp. (fern), *Leichhardtia australis* (climber)

Priority flora

This habitat is known to support a disproportionately high number of declared rare and priority species (Pringle et al. 1994; Payne et al. 1998b). *Allocasuarina eriochlamys* subsp. *grossa* (Priority 3), *Isopogon robustus* (Threatened), *Leucopogon validus* (Priority 1) and *Micromyrtus serrulata* (Priority 3) were recorded at 2 inventory sites. These species are typically not preferred by livestock, though it is not known whether goats graze them. Any areas where species of special conservation value occur may need to be managed for conservation.

Ecological disturbance

Long-term grazing impacts involve the removal of palatable shrub species, such as *Dodonaea rigida*, *Eremophila glabra* (tar bush), *E. latrobei* (warty fuchsia bush), *Ptilotus obovatus* (cotton bush) and *Sida calyxhymenia* (tall sida). However, their absence may also reflect the natural variability of this habitat and not necessarily indicate poor condition. Stony, indurated surfaces mean that erosion is generally not a problem.

Gradational associations

The exposed plateau surface and adjacent scarp face form a distinctive boundary between habitat types. Where vegetated, low breakaway scarps may border Breakaway footslope shrubland (BFSS, #8). On the upper slopes of some larger breakaways, BXSW may abut Lateritic eucalypt, non-halophytic woodland (LENW, #7). Back from the scarp and adjacent to sandplains, BXSW may border Sandplain acacia shrubland (SACS, #38) in the north-east of the survey, and Sandplain heathland (SAHE, #39) or Sandplain close mixed shrubland (SCMS, #40) in the west.

Land systems

BXSW is a major habitat type in the Cundlegum, Euchre, Eundynie and Gransal land systems and a minor habitat type in the Joseph and Kirgella land systems. Since indurated ferruginous surfaces can occur throughout the survey area, breakaways may also occur in other land systems, particularly on indurated rocks associated with the contact margins between greenstones and other rock types.

7 Lateritic eucalypt, non-halophytic woodland (LENW)

Sampling

6 inventory sites, 8 traverse points

General information

LENW is described for the first time. It occurs on gently to moderately inclined slopes associated with weathered ferruginous low rises or below breakaways capped by ferruginous duricrusts. A dense mantle of angular and subangular, coarse, ironstone gravels commonly covers the slopes. Soils are usually Shallow loamy gravel in higher landscape positions and Alkaline shallow duplex soils in lower colluvial positions.

LENW is similar to Eucalypt blackbutt grove or stand (EBBG, #17). However, EBBG is more often associated with calcareous loamy soils on very gently inclined low rises rather than steeper slopes with Loamy gravel soils, so the 2 habitat types are considered different.

Physiognomy and composition of vegetation

LENW usually occurs as a scattered to moderately close (>10–25% PFC) woodland or stands of *Eucalyptus lesouefii* (Goldfields blackbutt). Occasionally *Eucalyptus celastroides* subsp. *celastroides* and/or *E. salubris* (gimlet) may be co-dominant with *E. lesouefii.* The tall shrub stratum is typically absent or, like the mid shrub stratum, is only occupied by isolated individuals. The low shrub stratum is frequently dominated by *Eremophila pustulata* (warted eremophila). Perennial grasses are rare.

Lateritic eucalypt, non-halophytic woodland consisting of *Eucalyptus lesouefii* (Goldfields blackbutt) over *Eremophila pustulata* (warted eremophila) on loamy gravel on a footslope below a ferruginous duricrust in the Latimore land system

The dominant and common species by strata:

Trees:	Dominant – *Eucalyptus lesouefii*; occasionally *E. celastroides* subsp. *celastroides*, *E. salubris* Common – *Casuarina pauper* Other – *Acacia aneura* (in the north)
Tall shrubs:	Dominant – rarely present as a recognisable stratum Others – *Acacia tetragonophylla*, *Alyxia buxifolia*, *Dodonaea lobulata*, *Eremophila alternifolia*, *E. oppositifolia*, *Exocarpos aphyllus*, *Santalum spicatum*
Mid shrubs:	Dominant – rarely present as a recognisable stratum Common – *Atriplex nummularia* subsp. *spathulata*, *Eremophila scoparia* Others – *Maireana sedifolia*, *Senna artemisioides* subsp. *filifolia*
Low shrubs:	Dominant – *Eremophila pustulata* Common – *Acacia erinacea*, *Cratystylis microphylla*, *Maireana triptera*, *Olearia muelleri*, *Ptilotus obovatus*, *Scaevola spinescens* Others – *Eremophila glabra*, *Ptilotus helichrysoides*, *Westringia rigida*

Ecological disturbance

Since LENW also occurs outside the pastoral estate, the sparsity of the understorey may not be solely attributed to grazing pressure and other factors may be influencing the structure and composition. The sparse undergrowth may be singularly or synergistically a result of competition for water, extent of the tree canopy and root system, litter abundance and/or allelopathic inhibition. Despite the sparsity of understorey, LENW usually has good resistance to erosion because of the presence of an extensive stony mantle, except where vehicular activity has disturbed the surface.

Gradational associations

LENW usually has clearly defined boundaries, except where these communities may transition downslope into Gravelly eucalypt, non-halophytic woodland (GENW, #16) or occasionally mix with patches of Breakaway footslope shrubland (BFSS, #8). On vegetated breakaway plateaus, the upper slopes usually abut Breakaway mixed shrubland or woodland (BXSW, #6).

Land systems

LENW is a major habitat type in the Latimore land system and minor habitat type in the Illaara, Bevon and Monger land systems.

8 Breakaway footslope shrubland (BFSS)

Sampling

2 inventory sites, 6 traverse points

General information

BFSS is described for the first time. It occurs infrequently throughout the survey area in association with small duricrust remnants forming breakaway scarps over granite or greenstone parent material.

Physiognomy and composition of vegetation

BFSS consists of scattered low shrubland (>10–20% PFC) dominated by *Ptilotus helichrysoides*. Other low shrubs that occasionally share the footslopes include *Acacia erinacea*, *Eremophila parvifolia* subsp. *auricampa*, *Grevillea acuaria* and *Scaevola spinescens* (currant bush). The tall and mid shrub strata are usually absent. However, depending on the size and extent of the scarp, isolated individuals – species such as *Alyxia buxifolia* (dysentery bush), *Dodonaea lobulata* (bead hopbush), *Eremophila scoparia* (broom bush), *Exocarpos aphyllus* (leafless ballart) and *Santalum spicatum* (sandalwood) – from the plateau top or base may encroach onto the scarp face. Similarly, isolated individual trees that commonly encroach into BFSS include *Casuarina pauper* (black oak), *Eucalyptus celastroides* subsp. *celastroides* (mirret), *E. lesouefii* (Goldfields blackbutt), *E. stricklandii* (Strickland's gum) and *E. transcontinentalis* (redwood). Other plants occasionally present include the perennial herbs *Carpobrotus* spp. (pigface) and *Roepera apiculata* (gallweed).

Priority flora

This habitat type is known to support *Prostanthera splendens* (Priority 1).

Ecological disturbance

Not much is known about long-term grazing impacts and the scarcity of distribution make it difficult to confidently assess disturbance effects. It is susceptible to erosion if protective stone mantles are disturbed, for example, by construction of vehicle tracks and drill pads.

Gradational associations

BFSS generally has distinct boundaries defined by the scarp face of breakaways with a variety of well-defined plant communities above and below the scarp. Above the scarp face on breakaway plateaus, BFSS typically abuts Breakaway mixed shrubland or woodland (BXSW, #6). On the footslopes of some larger breakaways, BFSS may abut Lateritic eucalypt, non-halophytic woodland (LENW, #7). Downslope, at the scarp base, the vegetation may border either Breakaway footslope eucalypt woodland with chenopod understorey (BECW, #26), Plain eucalypt (mallee), acacia woodland (PEAW, #43) in the east, and Plain York gum, acacia woodland (PYAW, #44) in the west.

Land systems

BFSS is a minor habitat type in the Bannar, Cundlegum, Euchre, Gransal, Kanowna, Kurrawang, Latimore and Monger land systems.

Scattered low shrubland dominated by *Ptilotus helichrysoides* on a footslope below a ferruginous duricrust in the Latimore land system

9 Granite dome thicket (GRDT)

Sampling

5 inventory sites, 1 traverse point

General information

GRDT is described for the first time. It is found predominantly in the western half of the survey area on or adjacent to the bases of granite inselbergs, domes and outcrops. The capacity to capture watershed from rock outcrops influences the size of thickets, which usually range from 20 to 50 m across.

Granite inselbergs and domes support a complex of communities. Compared to most of the surface of granite domes, which are exposed and experience harsh conditions, these habitats are sheltered, fertile patches. The granites themselves may support Granitic acacia, *Borya* shrubland (GABS, #13), with mats of the perennial herb *Borya constricta* (resurrection plant) on soil classed as Bare rock. In moisture accumulation zones, thicket communities develop in pockets of deeper soil – Stony soil, Yellow–brown shallow sand and occasional Red deep sand – where moisture is retained longer. The flora usually differs from surrounding plains and may include attractive flowering species, such as *Kunzea pulchella* (granite kunzea) and *Melaleuca fulgens* subsp. *fulgens* (scarlet honeymyrtle). Granitic outcrop is extensive, and soils generally consist of coarse detrital matter washed off slopes, with noticeable dark colouring from accumulation of organic matter and cryptogam development.

Thickets associated with drainage foci on top of a large granite dome in the Wallaroo land system

Acacia thicket growing along a dam wall sited on a large granite dome. Uplifted and cemented exfoliated granite slabs channel watershed into the dam

Physiognomy and composition of vegetation

GRDT ranges from moderately close (>20% PFC) tall shrubland to closed (≥50% PFC) thickets with sparse mid and low shrub understoreys. This habitat is usually spatially restricted to small drainage foci, resulting in a high level of species richness. The floristic composition varies markedly around inselbergs and between outcrops. No individual species consistently dominates any stratum, except for *Acacia acuminata* (jam) and *A. lasiocalyx* (silver wattle) typically in the tall shrub stratum.

The dominant and common species by strata:

Trees:	Dominant – rarely present other than as emergents; occasionally *Acacia lasiocalyx*, *Allocasuarina huegeliana*
Mallees:	Dominant – rarely present other than as emergents; occasionally *Eucalyptus aspratilis*, *E. ewartiana, E. petraea* and *E. websteriana*
Tall shrubs:	Dominant – variable; often *Acacia acuminata*, *A. lasiocalyx*, *A. ramulosa* var. *ramulosa*, *Allocasuarina huegeliana* Common – *Kunzea pulchella*, *Santalum acuminatum*, *S. spicatum* Others – *Acacia jibberdingensis**, *A. tetragonophylla*, *Allocasuarina eriochlamys**, *Alyxia buxifolia*, *Calothamnus gilesii*, *Melaleuca elliptica**, *Melaleuca fulgens* subsp. *fulgens*
Mid shrubs:	Dominant – variable Common – *Dodonaea microzyga* var. *acrolobata*, *D. viscosa*, *Grevillea anethifolia*, *Senna artemisioides* subsp. *filifolia* Others – *Persoonia coriacea*, *Sida calyxhymenia* (KD)
Low shrubs:	Dominant – variable; occasionally *Ptilotus obovatus* Others – *Dampiera latealata*, *Prostanthera althoferi* subsp. *althoferi*, *Scaevola spinescens*, *Solanum lasiophyllum*
Perennial grasses:	Dominant – not present as a recognisable stratum Others – *Austrostipa scabra*, *Eriachne ovata*, *Spartochloa scirpoidea*
Other plant forms:	Occasional – *Borya constricta* (perennial herb), *Carpobrotus* spp. (succulent perennial herb), *Cassytha* spp. (climber), *Cheilanthes lasiophylla* (fern), *Dianella revoluta* (perennial herb), *Isotoma petraea* (perennial herb), *Lepidosperma* spp. (sedges)

* Also known from Newbey and Hnatiuk (1985, 1988)

Priority flora

Melaleuca macronychia subsp. *trygonoides* (Priority 3) was recorded near one site.

Ecological disturbance

Some granite domes have been used to supply water for historic wood harvesting, exploration and mining activities. Uplifted and cemented exfoliated granite slabs channel watershed into dams on or adjacent to the domes. These long-lasting water sources attract animals to these areas and grazing by native and introduced herbivores is likely to have locally influenced the composition of the surrounding vegetation. Palatable understorey species – for example, *Ptilotus obovatus* (cotton bush) and *Sida calyxhymenia* (tall sida) – could be removed under excessive grazing pressure. However, the natural variability in this habitat's flora makes it difficult to confidently assess grazing impacts. In most cases, the dominant plants are not particularly palatable or preferred by livestock.

Gradational associations

GRDT occurs as infrequent but distinct fertile patches in otherwise largely infertile upland landscapes and bears little resemblance to other habitat types. It may occur adjacent to Granitic acacia, *Borya* shrubland (GABS, #13). At the base or footslope of inselbergs, GRDT may transition into Sandy granitic acacia shrubland (SGRS, #11).

Land systems

GRDT is a minor habitat type in the Euchre, Kartukartunga, Norie, Sedgeman and Wallaroo land systems.

10 Granite hill mixed woodland (GRHW)

Sampling

3 inventory sites, 1 traverse point

General information

GRHW is similar to Granite hill mixed shrubland (GRHS) described in the north-eastern Goldfields (Pringle et al. 1994) and Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b) surveys. GRHW is described for the first time and considered different because of the presence of eucalypts and the increase in canopy cover of the tree and tall shrub strata.

GRHW is not common. It mainly occurs in the south-central parts of the survey on and around large exposures of granite expressed as domes or tor fields. It does not include the thickets associated with granite dome drainage foci, which are considered as a separate habitat, Granite dome thicket (GRDT, #9). Soil is Very shallow soil and limited to pockets of coarse detrital grit from the breakdown of talus dislodged by exfoliation through weathering.

Physiognomy and composition of vegetation

Vegetation varies in response to the amount of exposed granite, talus abundance and the extent of drainage foci development. GRHW typically consists of moderately close (>20–30% PFC) low woodland, with moderately close to close (30–50% PFC) patches of thicket, with mid and low shrubs of variable abundance in the understorey.

The dominant and common species by strata:

Trees:	Dominant – variable; occasionally *Eucalyptus lesouefii*
	Common – *Brachychiton gregorii*, *Casuarina pauper*
Mallees:	Dominant – variable; occasionally *Eucalyptus gracilis*
Tall shrubs:	Dominant – variable; occasionally *Acacia acuminata*, *A. quadrimarginea*
	Common – *Acacia tetragonophylla*, *Eremophila alternifolia*, *Exocarpos aphyllus*, *Santalum spicatum*
Mid shrubs:	Dominant – *Dodonaea lobulata*
	Common – *Senna artemisioides*
	Others – *Eremophila granitica*, *Melaleuca hamata*, *Sida calyxhymenia* (KD), *Thryptomene australis* subsp. *brachyandra*
Low shrubs:	Dominant – variable; occasionally *Ptilotus obovatus*
	Common – *Olearia muelleri, Scaevola spinescens* (KD)
	Others – *Enchylaena tomentosa* (KD), *Maireana georgei*, *Rhagodia drummondii* (KD), *Solanum lasiophyllum*
Perennial grasses:	Dominant – rarely present as a recognisable stratum
	Common – *Austrostipa scabra*
Other plant forms:	Common – *Cheilanthes lasiophylla* (fern), *Dianella revoluta* (perennial herb), *Leichhardtia australis* (climber), *Podolepis capillaris* (perennial herb)

Ecological disturbance

Goats and macropods are likely to be responsible for most grazing because GRHW is not considered a preferred habitat for livestock. Heavy grazing pressure may eliminate palatable perennial species, such as *Enchylaena tomentosa* (ruby saltbush), *Maireana georgei* (George's bluebush), *Ptilotus obovatus* (cotton bush), *Scaevola spinescens* (currant bush) and *Sida calyxhymenia* (tall sida). Erosion is unlikely because of the structural cohesiveness of the massive granite bodies, with exfoliation of granite sheets controlled by joint spacing and orientation.

Gradational associations

This habitat usually has clearly defined boundaries, though depending on the gradient of the granite dome footslope, GRHW may transition subtly into similar suites of non-halophytic dominated communities on some surrounding plains.

Land systems

GRHW is a major habitat type in the Sedgeman land system.

Granite hill mixed woodland at the base of a granite dome in the Sedgeman land system

B Stony plain and low rise non-halophytic shrubland or woodland habitats

These habitat types are common to granite-dominated uplands and surfaces with ferruginous duricrusts, though other substrates based on metasedimentary and greenstone deposits may also occur. They typically occur downslope of habitat types associated with prominent topography, such as hillslopes and footslopes, on etchplains (where the bedrock has been subject to considerable etching or subsurface weathering) grading downslope into sheetwash plains with stony mantles. Non-halophytic vegetation generally dominates the communities, with species from genera including *Acacia, Allocasuarina, Casuarina, Dodonaea, Eremophila, Ptilotus* and *Senna* being most common. Habitats often occur as very scattered to scattered tall shrublands with sparse understoreys, although eucalypt woodlands may occur where soil depth is not limiting.

These habitat types have relatively low to moderate pastoral value because of the sparsity of palatable species. Mineral exploration may disturb some of these habitat types, because of their proximity to ore deposits. While generally not susceptible to erosion where stony mantles are extensive, erosion can occur when surfaces on sloping gradients are disturbed by construction of exploration tracks and drill pads.

11 Sandy granitic acacia shrubland (SGRS)

Sampling

6 inventory sites, 50 traverse points

General information

SGRS is described in the north-eastern Goldfields (Pringle et al. 1994) and Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b) surveys. SGRS occurs almost exclusively on granite-dominated landscapes on very gently undulating, gritty-surfaced plains fringing granite domes, tors, pavements and quartz ridges. Soils are characteristically very shallow (<30 cm) soils and Red shallow sand or loam over granite. The soils are typically nutrient poor and the shallow depth limits water storage.

SGRS is restricted to the north of the survey area and represents granitoid vegetation associations typical of the Eremaean Botanical Province (Beard 1990) and Great Victoria Desert bioregion (Environment Australia 2000). With the southern transition into the South-western Interzone and Coolgardie bioregion, SGRS is gradually replaced by Granitic pediment eucalypt, tall shrub thicket (GETT, #12), Granitic acacia, *Borya* shrubland (GABS, #13) and Stony close jam shrubland (SCJS, #14) in the south and west of the survey.

Physiognomy and composition of vegetation

Vegetation is influenced by the extent of exposed granite. It typically occurs as a very scattered to scattered (5–20% PFC) tall shrubland, occasionally with the low shrub stratum being co-dominant. The mid shrub stratum is variable. Trees and perennial grasses are infrequent.

The dominant and common species by strata:

Trees:	Dominant – rarely present other than as emergents
	Others – *Brachychiton gregorii*, *Casuarina pauper*
Tall shrubs:	Dominant – *Acacia aneura*, *A. quadrimarginea*; occasionally *A. ramulosa* var. *ramulosa*
	Common – *Acacia burkittii*, *A. tetragonophylla*, *A. ramulosa* var. *ramulosa*
	Others – *Acacia acuminata*, *Santalum spicatum*
Mid shrubs:	Dominant – variable; *Acacia* (juveniles of tall shrubs) or *Eremophila* spp. most common
	Common – *Dodonaea lobulata*, *Eremophila clarkei*, *E. granitica*, *Senna artemisioides*, *S. artemisioides* subsp. *filifolia*, *Sida calyxhymenia* (KD)
	Others – *Dodonaea rigida* (KD), *D. viscosa*, *Eremophila serrulata*
Low shrubs:	Dominant – *Ptilotus obovatus*
	Common – *Enchylaena tomentosa* (KD), *Solanum lasiophyllum*
	Others – *Maireana planifolia* (KD), *M. triptera* (KD)
Perennial grasses:	Dominant – rarely present as a recognisable stratum
	Common – *Eriachne helmsii*
	Other – *Monachather paradoxus*
Other plant forms:	Common – *Cheilanthes sieberi* (fern)
	Other – *Borya constricta (perennial herb)*

Ecological disturbance

Condition assessments by Pringle et al. (1994) and Payne et al. (1998b) indicated considerable differences owing to natural variation, and to define the ungrazed state requires extensive sampling. Payne et al. (1998b) stated that in the Sandstone, Yalgoo and Paynes Find area survey 'more than half (59%) of the species recorded were not usually palatable to livestock, however, nearly three-quarters of the individual shrubs counted at condition sites were palatable. It is then quite possible for overgrazing to substantially alter this habitat'.

At certain times, SGRS can receive concentrated grazing pressure owing to the presence of gnamma holes and ephemeral rock pools of fresh water. On granite pavements where water remains for significant periods, habitats can be overgrazed to the detriment of the palatable plants. As with many habitat types, the early indicators of overgrazing would include a decrease in palatable species, such as *Enchylaena tomentosa* (ruby saltbush), *Dodonaea rigida*, *Maireana* spp. and *Sida calyxhymenia* (tall sida).

The stony, shallow soils and gently inclined gradients mean that water infiltration is limited and run-off can occur even after light rain. However, the shallow and coarse-grained nature of the soils means they are generally not susceptible to erosion and are stable.

Gradational associations

SGRS may form mosaics with Breakaway mixed shrubland or woodland (BXSW, #6) where remnant duricrust boulders are scattered over granitic pavements abutting collapsed breakaway scarps or transition into Granite dome thicket (GRDT, #9) at the base or footslopes of inselbergs. Downslope of pavements, as mantles disperse and soils become loamier, SGRS may transition into Plain eucalypt (mallee), acacia woodland (PEAW, #43) in the south, Hardpan plain mulga shrubland (HPMS, #47) in the north or Sandplain acacia shrubland (SACS, #38) in sandier landscapes. Elsewhere, SGRS usually has clearly defined boundaries.

Land systems

SGRS is a major habitat type in the Bandy, Gransal, Sedgeman land systems and a minor habitat type in the Cundlegum, Norie and Wallaroo land systems. It occurs infrequently in other land systems where granite pavements and rises occur.

Sandy granitic acacia shrubland on a gritty-surfaced plain underlain by granite pavement in the Bandy land system

12 Granitic pediment eucalypt, tall shrub thicket (GETT)

Sampling

10 inventory sites, 19 traverse points

General information

GETT is described for the first time. It typically occurs on very gently inclined pediments associated with granitoid pavements and low rises in the south of the survey area. GETT is similar to Stony close jam shrubland (SCJS, #14) with the main difference being the location and presence of eucalypts among acacia thickets. GETT tends to occur on pediment edges grading into colluvial sheetwash plains; whereas SCJS can be restricted to low rises and pavements.

Soils are usually Red shallow loam or Red sandy earth on the edge of granitic outcrop, with deeper soils of Red loamy earth and calcareous loams forming further from outcrop in the dominant land systems. Common evidence of proximity to bedrock is the angularity of the sand component in the soil, typically quartz, feldspar and plagioclase, and frequent granite gravels and stones in the mantle. Occasionally, the underlying rock is evident as outcrop.

As with SCJS, GETT replaces Sandy granitic acacia shrubland (SGRS, #11) in the south of the survey as granitoid vegetation associations typical of the Eremaean Botanical Province (Beard 1990) and Great Victoria Desert bioregion (Environment Australia 2000) transition southwards into the South-western Interzone and Coolgardie bioregion.

Physiognomy and composition of vegetation

GETT is a moderately close to closed (≥25% PFC) association characterised by scattered eucalypts among thickets of tall shrubs. Various mallee-form eucalypts occupy the tree stratum, ranging from very scattered to moderately close (5–25% PFC). The moderately close to close (25–50% PFC) thickets are frequently dominated by *Acacia burkittii* (sandhill wattle), though occasionally other *Acacia* spp., *Melaleuca* spp. or *Dodonaea lobulata* (bead hopbush) dominate. The mid and low shrub strata is variable and very scattered to scattered (5–20% PFC). Perennial grasses are infrequent.

Scattered eucalypts among thickets of *Acacia burkittii* (sandhill wattle) on a weathered granitic pediment in the Euchre land system

The dominant and common species by strata:

Trees and mallees:	Dominant – various *Eucalyptus* spp.; often *E. concinna*, *E. griffithsii*, *E. loxophleba* subsp. *lissophloia** or *E. oleosa* subsp. *oleosa*
Tall shrubs:	Dominant – *Acacia burkittii*; occasionally *A. acuminata*, *A. quadrimarginea*, *A. ramulosa* var. *ramulosa, Dodonaea lobulata* or *Melaleuca* spp.
	Common – *Eremophila oppositifolia*, *Exocarpos aphyllus*
	Others – *Acacia colletioides*, *A. ligulata*, *A. prainii*, *A. tetragonophylla*, *Alyxia buxifolia*, *Melaleuca* spp., *Santalum spicatum*
Mid shrubs:	Dominant – variable; often *Dodonaea lobulata,* occasionally *Eremophila* spp.
	Common – *Eremophila granitica*, *Senna artemisioides* subsp. *filifolia*
	Others – *Eremophila decipiens*, *E. scoparia*, *Prostanthera althoferi* subsp. *althoferi*
Low shrubs:	Dominant – variable
	Common – *Olearia muelleri*, *Olearia pimeleoides*, *Ptilotus obovatus*, *Scaevola spinescens*, *Solanum lasiophyllum*
	Others – *Acacia erinacea*, *Enchylaena tomentosa* (KD), *Grevillea acuaria*, *Maireana georgei* (KD), *M. triptera*, *Prostanthera grylloana*
Perennial grasses:	Dominant – not present as a recognisable stratum
	Common – *Austrostipa scabra*
	Others – *Austrostipa elegantissima*, *Monachather paradoxus*
Other plant forms:	Common – *Leichhardtia australis* (climber), *Ptilotus exaltatus* (annual herb)

* Also known from Newbey and Hnatiuk (1985, 1988); Newbey et al. (1995)

Priority flora

Melaleuca coccinea (Priority 3) was recorded at one site.

Ecological disturbance

Like SCJS, GETT supports few palatable species and does not appear to be significantly affected by grazing. It is not particularly susceptible to erosion in areas with an extensive mantle or while the protective coverage from dense thickets remains intact. However, when the edges of pediments are driven on when the soil is damp, vehicle tracks may form ruts which can subsequently initiate terrace erosion perpendicular to gradients.

Gradational associations

Upslope, where soils become shallower as outcrop becomes more exposed, boundaries are usually clearly defined. Downslope of pediments, GETT transitions into Plain eucalypt (mallee), acacia woodland (PEAW, #43), Colluvial slope eucalypt woodland over non-halophytic shrubland (CEWS, #51) or Plain eucalypt, eremophila woodland (PEEW, #59).

Land systems

GETT is a major habitat type in the Dunnsville and Euchre land systems and a minor habitat type in the Johnston, Sedgeman and the southernmost occurrences of the Bandy and Kirgella land systems.

13 Granitic acacia, *Borya* shrubland (GABS)

Sampling

3 inventory sites, 1 traverse point

General information

GABS is an uncommon habitat type in this survey area. It was first described in the Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b) and is similar to Sandy granitic acacia shrubland (SGRS, #11). Payne et al. (1998b) consider GABS represents a regional variation grading away from the Eremaean Botanical Province (Beard 1990) and Yalgoo bioregion (Environment Australia 2000) into the South-western Interzone and Coolgardie bioregion. Vegetation cover is sometimes greater than SGRS owing to the dense mats of *Borya constricta* (resurrection plant). Soils are Very shallow (<30 cm) soil and Red or Yellow shallow sand soils between low (usually less than 5 m) granite outcrops.

Physiognomy and composition of vegetation

GABS is characterised by *Borya constricta* which can range from isolated individuals to dense mats on soil accumulation zones or adjacent to granitic pavements. It is usually associated with scattered to moderately close (15–30% PFC) tall shrubland where mats are not dominant. Trees and perennial grasses are not well represented in this relatively infertile habitat. The tall shrub stratum often consists of moderately close (25–30% PFC) thickets of *Acacia acuminata* (jam), *A. burkittii* (sandhill wattle), *A. lasiocalyx* (silver wattle), *A. ramulosa* var. *ramulosa* or *Allocasuarina* spp., depending on floristic regional distribution. Other tall shrubs frequently present, but as isolated individuals, include *Alyxia buxifolia* (dysentery bush), *Dodonaea viscosa* (sticky hopbush), *Eremophila oppositifolia*, *Santalum acuminatum* (quandong), *S. spicatum* (sandalwood) and *Thryptomene australis* subsp. *brachyandra*. The mid and low shrub strata is often scattered (>10–20% PFC), with variable composition. Common species include *Eremophila granitica* (thin-leaved poverty bush), *Olearia muelleri* (Goldfields daisy), *O. pimeleoides* (pimelea daisybush), *Prostanthera grylloana*, *Scaevola spinescens* (currant bush) and *Senna artemisioides* subsp. *filifolia* (desert cassia). Other plant forms include *Cheilanthes* spp. (ferns), *Dianella revoluta* (perennial herb), *Isotoma petraea* (perennial herb), *Lepidosperma* spp. (sedges), the perennial *Austrostipa elegantissima* (feather speargrass) and annual *Aristida contorta* (bunched kerosene grass).

Dense mat of *Borya constricta* (resurrection plant) on a granitic pavement in the Sedgeman land system

Gradational associations

GABS is a distinctive habitat type which usually has clearly defined boundaries. As sand sheets coalesce over granite outcrop, GABS is replaced by SGRS, particularly in the north, and Stony close jam shrubland (SCJS, #14) in the south of the survey. GABS is replaced by Granite dome thicket (GRDT, #9) in accumulation zones with good soil moisture retention characteristics.

Land systems

GABS is a minor habitat type in the Bandy, Euchre, Joseph and Sedgeman land systems.

14 Stony close jam shrubland (SCJS)

Subtype: Jam shrubland over spinifex (JASP)

Sampling

SCJS: 13 inventory sites, 68 traverse points

JASP: 12 traverse points

General information

SCJS was first described in the Kambalda survey (Payne et al. 1998a). In the southern Goldfields, it commonly occurs in granite-dominated landscapes in the south, and on surface expressions of dolerite dykes or low rises associated with metasedimentary rocks. Sometimes the underlying rock is evident in outcrop or stony mantle, while in other locations the only evidence of bedrock is a surface strew of coarse quartz sand or grit. Soils are typically red, Very shallow soil and Red shallow loam over granite, and less commonly Red–brown hardpan shallow loam or Very shallow soil over ferruginous duricrust.

SCJS replaces Sandy granitic acacia shrubland (SGRS, #11) in the south as granitoid vegetation associations more typical of the Eremaean Botanical Province (Beard 1990) and Great Victoria Desert bioregion (Environment Australia 2000) transition southwards into the South-western Interzone and Coolgardie bioregion. SCJS has floristic similarities to Granitic pediment eucalypt, tall shrub thicket (GETT, #12), with the primary difference being the prominence of eucalypts among the acacia thickets and the restriction of SCJS to low rises and pavements; GETT tends to grade downslope from pediments into colluvial, sheetwash plains.

A subtype of SCJS is Jam shrubland over spinifex (JASP). While JASP is relatively similar to SCJS, it is distinguished by the presence of *Triodia scariosa* (spinifex) in the grass stratum among thickets of *Acacia burkittii* (sandhill wattle). JASP occurs in the east of the survey on the rises and pediments of the Yandamurrina land system associated with Fraser Range.

Physiognomy and composition of vegetation

SCJS is dominated by the tall shrub stratum, which can grow to 6 m. It typically occurs as moderately close to closed (≥25% PFC) thickets, though occasionally SCJS may be slightly more open (15–20% PFC) because of the presence of surface bedrock. It is characterised predominantly by *Acacia acuminata* (jam) or less commonly *A. burkittii* in the tall shrub layer. A variation of SCJS lacks these acacias and is instead dominated by *A. duriuscula*. Trees, if present, are very scattered (<5% PFC). The mid shrub layer is very scattered to scattered (5–15% PFC). The low shrub layer is variable (2.5–30% PFC). Perennial grasses are sparse.

The dominant and common species by strata:

Trees and mallees:	Dominant – rarely present other than as emergents Others – *Acacia aneura* (in the north), *Brachychiton gregorii*, *Eucalyptus griffithsii*, *E. loxophleba* subsp. *lissophloia*
Tall shrubs:	Dominant – *Acacia acuminata*, *A. burkittii*; occasionally *A. duriuscula* or *A. ramulosa* var. *ramulosa* Common – *Acacia ramulosa* var. *ramulosa*, *A. tetragonophylla*, *Dodonaea lobulata*, *Melaleuca hamata* Other – *Eremophila alternifolia*
Mid shrubs:	Dominant – *Acacia acuminata*, *A. burkittii* Common – *Beyeria sulcata* var. *sulcata*, *Dodonaea lobulata*, *Senna artemisioides* subsp. *filifolia* Others – *Eremophila decipiens*, *Pimelea microcephala*, *Prostanthera althoferi* subsp. *althoferi*
Low shrubs:	Dominant – variable Common – *Enchylaena tomentosa* (KD), *Olearia pimeleoides*, *Ptilotus obovatus*, *Scaevola spinescens* Others – *Maireana georgei*, *Olearia muelleri*, *Prostanthera grylloana*, *Solanum lasiophyllum*
Perennial grasses:	Dominant – *Triodia scariosa* in JASP subtype Common – *Austrostipa elegantissima*
Other plant forms:	Common – *Dianella revoluta* (perennial herb), *Leichhardtia australis* (climber)

Priority flora

Melaleuca coccinea (Priority 3) and *Micromyrtus serrulata* (Priority 3) were recorded at one site each.

Ecological disturbance

SCJS does not appear to be affected by grazing because it supports few palatable species, particularly when the acacia thickets are dense. SCJS is not particularly susceptible to erosion because of the stony shallow soils.

Gradational associations

SCJS is a distinctive habitat type, usually with clearly defined boundaries.

Moderately close tall shrubland of *Acacia burkittii* (sandhill wattle) on a low mafic rise in the Gundockerta land system

Land systems

SCJS is the dominant habitat type in the Binneringie and Zed land systems, a major habitat type in Sedgeman land system and a minor habitat type in the most southern occurrences of Bandy and Kwelkan land systems. It occurs infrequently in other land systems where there are surface expressions of dolerite dykes or pavements and rises of granitic or metasedimentary rocks. JASP is restricted to the Yandamurrina land system, where it occurs as a minor habitat type.

15 Stony casuarina, dodonaea shrubland (SCDS)

Sampling

27 inventory sites, 135 traverse points

General information

SCDS is described for the first time. It is associated with low hills and rises scattered throughout the centre of the survey area. Occurring on mafic, granitic and metasedimentary rocks, SCDS is especially common on ferruginous rocks. A dense mantle of angular, subangular and/or subrounded stones and gravels of mixed size, derived from the underlying bedrock and then indurated by iron, is usually present. Soils vary, but can be identified by their bedrock constitution, weathering history and landscape position. On crests of hills and rises, underlain by unweathered rock, very shallow soils are present. Similar landscape positions in deeply weathered terrain result in Very shallow soil over ferruginous duricrust. Where bedrock is calcium-rich, the calcareous variants of the soils are present. Further downslope, soils generally become deeper and form Very shallow soil over hardpan on felsic basement or Calcareous gravelly shallow loam on basic basement. Lower slope soils are deeper again and commonly are Calcareous loamy earth, Alkaline red shallow loamy duplex and Calcareous loamy ironstone gravel soils.

Physiognomy and composition of vegetation

SCDS occurs as a scattered to moderately close (>10–30% PFC) tall shrubland. The tree stratum consists of predominantly very scattered to scattered (>2.5–20% PFC) *Casuarina pauper* (black oak). The understorey is typically dominated by *Dodonaea lobulata* (bead hopbush) or is co-dominant with *Scaevola spinescens* (currant bush) or *Senna artemisioides* subsp. *filifolia* (desert cassia). The tall and mid shrub strata are variably developed, being very scattered to moderately close (10–25% PFC), with understorey development inversely related to coverage by upper strata. The low shrub stratum is typically very scattered (>2.5–10% PFC).


Variations of Stony casuarina, dodonaea shrubland: left) a community on a ferruginous low rise; right) a footslope of a metasedimentary ridge

The dominant and common species by strata:

Trees:	Dominant – *Casuarina pauper* Common – *Acacia aneura*
Tall shrubs:	Dominant – *Acacia* spp., *Dodonaea lobulata*; occasionally *Eremophila* spp. Common – *Acacia aneura*, *A. burkittii*, *A. ligulata*, *A. tetragonophylla*, *Alyxia buxifolia*, *Eremophila alternifolia*, *Exocarpos aphyllus*, *Santalum spicatum* Others – *Acacia hemiteles*, *A. quadrimarginea*, *Alectryon oleifolius*, *Eremophila oldfieldii*, *E. oppositifolia*
Mid shrubs:	Dominant – *Dodonaea lobulata*; occasionally *Scaevola spinescens*, *Senna artemisioides* subsp. *filifolia* Common – *Scaevola spinescens*, *Senna artemisioides* subsp. *filifolia* Others – *Atriplex nummularia* subsp. *spathulata*, *Eremophila decipiens*, *E. glabra*, *E. latrobei* (KD), *Sida calyxhymenia* (KD)
Low shrubs:	Dominant – variable; occasionally *Acacia erinacea*, *Olearia muelleri*, *Ptilotus obovatus*, *Scaevola spinescens* Common – *Acacia erinacea*, *A. hemiteles*, *Enchylaena tomentosa* (KD), *Maireana sedifolia*, *M. triptera*, *Olearia muelleri*, *Ptilotus obovatus*, *Scaevola spinescens* (KD), *Solanum lasiophyllum* Others – *Eremophila parvifolia* subsp. *auricampa* (KD), *Maireana convexa* (KD) in the north, *M. georgei* (KD)
Perennial grasses:	Dominant – not present as a recognisable stratum Others – *Austrostipa elegantissima*, *A. platychaeta*, *A. scabra*
Other plant forms:	Common – *Leichhardtia australis* (climber) Other – *Amyema linophylla* subsp. *linophylla* (mistletoe)

Priority flora

Thryptomene eremaea (Priority 2) was recorded at one site.

Ecological disturbance

The composition and density of palatable low shrubs in SCDS is naturally variable. However, some of the following palatable species should be present: *Enchylaena tomentosa* (ruby saltbush), *Eremophila latrobei* (warty fuchsia bush), *E. parvifolia* subsp. *auricampa*, *Maireana convexa* (mulga bluebush) in the north, *M. georgei* (George's bluebush), *Ptilotus obovatus* (cotton bush) and *Sida calyxhymenia* (tall sida). Communities devoid of these plants can be assumed to have been substantially altered by grazing. The exception is *P. obovatus* whose abundance and occurrence can also be influenced by seasonal conditions and natural spatial variability; its absence does not necessarily indicate poor condition. SCDS is not preferentially grazed by livestock, but it may be frequented by feral goats and large populations will cause a decline in condition. Coverage by an unpalatable, tall shrub stratum over dense stony mantles provides effective protection against erosion.

Gradational associations

SCDS may merge with upslope habitat types, such as Greenstone hill acacia shrubland (GHAS, #1) on greenstone hills, or abut Casuarina ridge woodland (CRIW, #5) where ferruginous rocks contact metasedimentary ridges. It often transitions downslope into Sandy granitic acacia shrubland (SGRS, #11) near granitic pavements; Stony plain bluebush mixed shrubland (SBMS, #32) on alluvial fans; and Plain eucalypt (mallee), acacia woodland (PEAW, #43) on marginal plains. SCDS is distinct and usually has clearly defined boundaries where footslopes or rises abut chenopod communities.

Land systems

SCDS is common through the centre of the survey area and features in many land systems on hillslopes and rises, particularly when associated with greenstone or ferruginous landforms. It is a major habitat type in the Gransal, Illaara, Kurrawang, Monger and Moriarty land systems and a minor habitat type in the Bevon, Graves, Gundockerta, Hampton, Latimore and Lawrence land systems.

16 Gravelly eucalypt, non-halophytic woodland (GENW)

Sampling

17 inventory sites, 103 traverse points

General information

GENW is described for the first time. It typically occurs on the footslopes of low hills and rises associated with greenstones and ferruginous rocks, as well as remnant low rises on plains. GENW is associated with a range of soil types that are shallow or very shallow with appreciable coarse fragments and gravel within a calcareous soil matrix, although a minority of soils have a neutral to slightly acidic soil matrix. The most common soils are Shallow loamy gravel and Calcareous loamy ironstone gravel, Very shallow calcrete/hardpan soil, Calcareous stony soil and Calcareous shallow loam. A dense mantle of subrounded, medium to coarse (6–60 mm) ironstone gravels and/or subangular cobbles of ferricrete forms the surface. Sparse outcrop is occasionally present, usually consisting of ferricrete, calcrete or metasedimentary rocks.

It has some similarity with Greenstone hill eucalypt woodland (GHEW, #2) and in some instances is intermediary on footslopes between GHEW on the hillslopes above and various eucalypt woodland associations on the adjacent plains below. The primary differentiating factors are gradient, soil type, depth and stone content, and dominant eucalypts.

Physiognomy and composition of vegetation

GENW occurs as a scattered to moderately close (15–30% PFC) eucalypt woodland over non-halophytic shrubs. The tree stratum ranges from scattered to moderately close (>10–30% PFC). The tall and mid shrub strata vary from very scattered to moderately close (10–25% PFC), usually inversely related to tree coverage. The low shrub stratum is typically very scattered to scattered (>2.5–15% PFC). Perennial grasses only grow among shrubs.

Gravelly eucalypt, non-halophytic woodland dominated by *Eucalyptus griffithsii* (Griffith's grey gum) on a low rise in the Illaara land system

Like GHEW, variability is influenced by the underlying geology, soil depth and topography associated with these stony habitats. Typically these woodlands are dominated by *Eucalyptus griffithsii* (Griffith's grey gum) or *E. lesouefii* (Goldfields blackbutt), though occasionally the tree stratum may be dominated or co-dominated by other eucalypts.

The dominant and common species by strata:

Trees and mallees:	Dominant – *Eucalyptus griffithsii*, *E. lesouefii*; occasionally *E. oleosa* subsp. *oleosa*
	Common – *Casuarina pauper*
	Others – *Eucalyptus celastroides* subsp. *celastroides*, *E. clelandiorum*, *E. salmonophloia*, *E. salubris* (lower footslopes)
Tall shrubs:	Dominant – variable; *Acacia* spp., *Dodonaea* spp., *Eremophila* spp., *Melaleuca* spp.
	Common – *Acacia burkittii*, *A. tetragonophylla*, *Alyxia buxifolia*, *Dodonaea lobulata* (KI), *Eremophila interstans* subsp. *interstans*, *E. oppositifolia*, *E. scoparia* (KI), *Exocarpos aphyllus*, *Santalum acuminatum*, *S. spicatum*
	Others – *Acacia acuminata*, *Eremophila alternifolia*, *Melaleuca* spp.
Mid shrubs:	Dominant – variable; *Dodonaea lobulata* (KI), *Eremophila scoparia* (KI), *Senna artemisioides* subsp. *filifolia* (KI)
	Common – *Acacia hemiteles* (KI), *Atriplex nummularia* subsp. *spathulata*, *Scaevola spinescens*
	Others – *Dodonaea* spp., *Eremophila glabra* (KD), *E. granitica*
Low shrubs:	Dominant – *Scaevola spinescens*; occasionally *Olearia muelleri*
	Common – *Acacia erinacea*, *Maireana triptera*, *Olearia muelleri*, *Ptilotus obovatus*
	Others – *Atriplex vesicaria* (KD), *Enchylaena tomentosa* (KD), *Eremophila parvifolia* subsp. *auricampa* (KD), *Grevillea acuaria*, *Solanum orbiculatum*, *Westringia rigida*
Perennial grasses:	Dominant – rarely present as a recognisable stratum
	Common – *Austrostipa elegantissima* (KD), *A. scabra*
Other plant forms:	Common – *Sclerolaena diacantha* (perennial herb)
	Occasional – *Leichhardtia australis* (climber)

Ecological disturbance

GENW habitats predominantly support unpalatable shrubs, so they are unlikely to be significantly affected by grazing, except for uncontrolled goat populations that may frequent these landforms. Historic grazing effects may be responsible for present species composition. In many areas, unpalatable species – such as *Dodonaea lobulata* (bead hopbush), *Eremophila scoparia* (broom bush) and *Senna artemisioides* subsp. *filifolia* (desert cassia) – dominate the mid shrub stratum, with much recruitment also occurring in the low shrub stratum. Palatable species – such as *Austrostipa elegantissima* (feather speargrass), *Eremophila glabra* (tar bush), *E. parvifolia* subsp. *auricampa* and *Ptilotus obovatus* (cotton bush) – are usually infrequent and their abundance may have been affected through overgrazing. The abundance of *P. obovatus* is influenced by seasonal conditions and is naturally spatially variable, so its absence does not necessarily indicate poor condition. More reliable condition indicators generally occur on the lower slopes of rises and footslopes, adjacent to plains, where there are often more of the palatable species, such as *Atriplex vesicaria* (bladder saltbush) and *Sclerolaena diacantha* (grey bindii). The stony and gravelly mantles of GENW habitats provide effective protection against erosion, unless there has been disturbance from vehicles, drill pads and costeans.

Gradational associations

On footslopes, GENW may transition upwards into GHEW or Greenstone hill acacia shrubland (GHAS, #1) as species composition in the tree and tall shrub strata changes, or into Greenstone mallee, spinifex woodland (GMSW, #3) where spinifex becomes the dominant understorey plant replacing the mid and low shrub strata.

On some ferruginous rises, GENW may transition into usually distinct habitat types, such as Eucalypt blackbutt grove or stand (EBBG, #17) or Lateritic eucalypt, non-halophytic woodland (LENW, #7). Elsewhere, GENW usually has clearly defined boundaries.

Land systems

GENW is a major habitat type in the Illaara and Monger land systems and a minor habitat type in the Coolgardie, Graves, Hampton, Kurrawang and Moriarty land systems. It also features infrequently on occasional low rises in many other land systems.

17 Eucalypt blackbutt grove or stand (EBBG)

Sampling

7 inventory sites, 61 traverse points

General information

EBBG is described for the first time. It most frequently occurs on very gently inclined low rises in the Kambalda and Dundas zones on Calcareous gravelly shallow loam and Calcareous (gravelly) loamy earth soils. It is also associated with ferruginous rises on Loamy gravel soils. In the central-east of the survey area in the Dundas Zone in the Eundynie land system, EBBG occurs on low rises of ferruginous sedimentary rocks on Calcareous stony soil. An extensive coverage of stones and gravels of mixed shape and size often forms a mantle, regularly consisting of calcrete or ironstone, though other rock types derived from the underlying bedrock may also be present. The ground around tree bases often has a dense covering of leaf litter.

Low rises supporting stands of *Eucalyptus lesouefii* (Goldfields blackbutt) over sparse understorey and dense leaf litter layer

Physiognomy and composition of vegetation

EBBG usually occurs as a moderately close to close (>20–50% PFC) grove or stand of *Eucalyptus lesouefii* (Goldfields blackbutt) on the upper slopes and crests of low rises. Other eucalypts of similar form, such as *E. clelandiorum* (Cleland's blackbutt), may occur instead of *E. lesouefii.* Other strata are rarely dominant, and species present usually occur as isolated individuals or are very scattered. Infrequent patches of woodland with similar physiognomy and composition as EBBG also occur, but these are on level surfaces and slightly more extensive than the clustered groves on convex rises.

The dominant and common species by strata:

Trees:	Dominant – *Eucalyptus lesouefii*; occasionally *E. clelandiorum* Common – *Casuarina pauper*
Tall shrubs:	Dominant – rarely present as a recognisable stratum; occasionally *Eremophila* spp. Common – *Acacia hemiteles*, *A. tetragonophylla*, *Dodonaea lobulata*, *Eremophila alternifolia*, *E. interstans* subsp. *interstans*, *E. scoparia*, *Exocarpos aphyllus*
Mid shrubs:	Dominant – rarely present as a recognisable stratum Common – *Atriplex nummularia* subsp. *spathulata*, *Eremophila glabra*, *E. scoparia*, *Maireana sedifolia*, *Senna artemisioides* subsp. *filifolia*
Low shrubs:	Dominant – rarely present as a recognisable stratum Common – *Acacia erinacea*, *Eremophila parvifolia* subsp. *auricampa*, *E. pustulata*, *Maireana triptera*, *Olearia muelleri*, *Ptilotus obovatus*, *Scaevola spinescens*
Other plant forms:	Common – *Sclerolaena diacantha* (perennial herb)

Ecological disturbance

The sparse understorey of EBBG is distinctive. This sparseness also occurs in EBBG outside of pastoral leases, so it is likely other factors besides grazing pressure influence the physiognomy and composition. The suppression of undergrowth may be singularly or synergistically a result of competition for water, extent of the tree canopy and root system, litter abundance and/or allelopathic inhibition, similar to the allelopathic effects reported for *Eucalyptus dundasii* (Wu et al. 2011; Zhang et al. 2012).

The presence of an extensive stony mantle, in conjunction with a dense leaf litter layer, usually offers effective protection against erosion, unless vehicular activity causes disturbance, whereby surfaces on calcareous soils can become unstable.

Gradational associations

EBBG may transition subtly downslope into Gravelly eucalypt, non-halophytic woodland (GENW, #16) in non-halophytic dominated communities or Greenstone eucalypt, saltbush woodland (GESW, #28) on rises associated with ultramafic deposits and where *Atriplex* species increase in prominence. Elsewhere, this habitat usually has clearly defined boundaries.

Land systems

EBBG features in many land systems on low rises throughout the Kambalda Zone and infrequently in the Mount Jackson Plains and Hills Zone. It is a major habitat type in the Eundynie and Monger land systems and a minor habitat type in the Illaara, Kanowna, Kurrawang and Moriarty land systems.

18 Lateritic allocasuarina scrub (LASC)

Subtype: Lateritic allocasuarina scrub – gravel (LASC–G)

Subtype: Lateritic allocasuarina scrub – hill (LASC–H)

Sampling

LASC–G: 5 inventory sites, 17 traverse points

LASC–H: 6 inventory sites, 1 traverse point

General information

LASC is described for the first time. These habitat types are characterised by *Allocasuarina*-dominated shrublands. LASC was treated as the broad habitat type, but it was split into 2 subtypes to provide landform-specific information.

- LASC–G is associated with gravelly sand sheets, which are usually marginal to sandplains or on low gravelly rises within sandplains. Soils are Shallow sandy – and loamy – gravel and Loamy gravel, with occasional Deep sandy gravel.
- LASC–H occurs on hills and low rises associated with ferruginised duricrusts, BIFs and occasionally basalt. Landscape position influences soil type: crests have Bare rock (infrequent basalt or ferruginised rock outcrop); and slopes have Very shallow ironstone soil. The surface comprises an extensive mantle of subangular to subrounded, medium to coarse (6–60 mm) gravels consisting of ferricrete and ironstone.

The *Allocasuarina* species dominating LASC habitat types are variable and influenced by topography, geology and regional distribution. While some *Allocasuarina* species often occur on certain landforms throughout the survey area, others have limited distribution. The floristic composition of these habitats may be influenced by adjacent landforms, so is often variable.

Allocasuarina-dominated shrubland (LASC–G) on a low gravelly rise, marginal to a sandplain, in the Bannar land system

Allocasuarina-dominated shrubland (LASC–H) on a banded iron formation ridge crest in the Dryandra land system

Physiognomy and composition of vegetation – LASC–G

On low gravelly rises and gravelly sands marginal to sandplains, *Allocasuarina corniculata* frequently dominates LASC–G. The tall shrub stratum ranges from scattered to moderately close (>10–30% PFC), with shrub density influencing understorey development. Mature LASC–G communities often have a very scattered (>2.5–10% PFC) mid and low shrub understorey. The tree stratum may be occupied by scattered (>10–20% PFC) mallees. Isolated to scattered (<15% PFC) hummocks of *Triodia* spp. (spinifex) are often present. Species common to other sandplain habitat types occur infrequently.

The dominant and common species by strata:

Mallees:	Dominant – rarely present other than as emergents; occasionally *Eucalyptus concinna*, *E. griffithsii, E. loxophleba* subsp. *lissophloia*
Tall shrubs:	Dominant – *Allocasuarina corniculata*; occasionally *A. acutivalvis* subsp. *prinsepiana*, *A. eriochlamys**, *A. helmsii* Common – *Alyxia buxifolia*, *Melaleuca hamata* Others – *Acacia coolgardiensis**, *A. resinimarginea*, *A. tetragonophylla*, *Callitris preissii**, *Santalum acuminatum*
Mid shrubs:	Dominant – juvenile *Allocasuarina* spp., otherwise rarely present as a recognisable stratum Common – *Eremophila granitica*, *Melaleuca hamata* Others – *Dodonaea* spp., *Eremophila georgei*, *Persoonia coriacea*, *Philotheca brucei*
Low shrubs:	Dominant – rarely present as a recognisable stratum Common – *Stenanthemum stipulosum* Others – *Cryptandra aridicola*, *Melaleuca cordata*, *Phebalium filifolium**, *Prostanthera* spp., *Scaevola spinescens*, *Westringia cephalantha*
Perennial grasses:	Dominant – rarely present as a recognisable stratum Common – *Triodia* spp.; occasionally *T. irritans*, *T. scariosa**, *T. tomentosa* Other – *Austrostipa elegantissima*
Other plant forms:	*Lepidobolus preissianus** (sedge), *Lepidosperma drummondii** (sedge)

* Also known from Newbey and Hnatiuk (1985, 1988); Newbey et al. (1995)

Priority flora

Grevillea erectiloba (Priority 4) was recorded at one site.

Physiognomy and composition of vegetation – LASC–H

On the greenstone and BIF hills in the west (those associated with the Dryandra, Greenmount and Jaurdi land systems), *Allocasuarina acutivalvis* subsp. *acutivalvis* is most common, forming moderately close to close (25–50% PFC) homogenous thickets. On ridges and hillslopes, the tree stratum is rare. The mid and low shrub strata may be absent or only sparsely occupied by isolated individuals, though in some instances, other species (such as *Melaleuca hamata*) are very abundant. Genera, such as *Calothamnus*, *Cryptandra*, *Dodonaea*, *Prostanthera* and *Stackhousia*, occur infrequently but with different species across the region.

The dominant and common species by strata:

Trees and mallees:	Dominant – rarely present as a recognisable stratum; occasionally *Eucalyptus clelandiorum*, *E. yilgarnensis*
Tall shrubs:	Dominant – *Allocasuarina acutivalvis* subsp. *acutivalvis*; occasionally *A. eriochlamys**, *A. eriochlamys* subsp. *eriochlamys*, *A. huegeliana* Others – *Acacia burkittii*, *A. tetragonophylla*, *A. quadrimarginea**, *Alyxia buxifolia*, *Calothamnus* spp., *Hakea subsulcata*, *Santalum acuminatum*
Mid shrubs:	Dominant – juvenile *Allocasuarina* spp., otherwise not present as a recognisable stratum Common – *Melaleuca hamata*

	Others – *Dodonaea* spp., *Eremophila georgei*, *Gastrolobium spinosum*, *Grevillea georgeana*, *Philotheca brucei*
Low shrubs:	Dominant – not present as a recognisable stratum
	Others – *Cryptandra* spp., *Melaleuca cordata*, *Olearia muelleri*, *Prostanthera* spp., *Scaevola spinescens*, *Stackhousia* spp., *Stenanthemum stipulosum*
Perennial grasses:	Dominant – not present as a recognisable stratum
	Other – *Austrostipa elegantissima*
Other plant forms:	Common – *Cassytha melantha* (climber)
	Other – *Cheilanthes* spp.* (fern)

* Also known from Newbey and Hnatiuk (1984, 1988); Newbey et al. (1995)

Priority flora

Acacia singula (Priority 3) and *Hibbertia lepidocalyx* subsp. *tuberculata* (Priority 3) were recorded at one site each.

Ecological disturbance

LASC habitat types generally appear to be stable. They are not particularly affected by grazing as they consist of predominantly unpalatable species. Where a stony mantle is present, susceptibility to erosion is reduced unless there is disturbance – such as with exploration tracks and drill pad construction – and the vegetation density provides protection against wind erosion.

LASC–G, like other habitat types with similar dense, tall shrub assemblages (i.e. Sandplain close mixed shrubland), tend to become more flammable as spatial patterning becomes more contiguous and fuel loads develop with time. However, LASC–H habitats often have long intervals between fires, with modelling of these scrub–thickets indicating timescales of a fire regime equal to 101 years (O'Donnell et al. 2011a). These long fire intervals in LASC–H seem to be partially controlled by natural barriers, such as the rocky substrate on which the associations occur and being surrounded by woodlands with limited fuel loads, thereby reducing the probability of burning (O'Donnell et al. 2011a).

Gradational associations

At sandplain margins, LASC–G often transitions into Sandplain heathland (SAHE, #39) or Sandplain close mixed shrubland (SCMS, #40) as sand depth increases and gravel content diminishes with species of *Allocasuarina* becoming less prominent.

Since LASC–H is typically associated with ferruginous, stony landforms, it usually has clearly defined boundaries. However, where BIFs and ferruginous duricrusts abut greenstones, LASC–H may form a patch mosaic with, or become replaced by, Greenstone hill acacia shrubland (GHAS, #1) or Greenstone hill eucalypt woodland (GHEW, #2), as acacias or eucalypts, respectively, replace allocasuarina as dominant. Where spinifex abundance increases, Allocasuarina, spinifex scrub–thicket (ASST, #4) becomes prevalent.

Land systems

LASC–G is a major habitat type in the Bannar and Hyden land systems. It is uncommon in sandplains, such as the Joseph land system. Inventories by Newbey and Hnatiuk (1985, 1988) and Newbey et al. (1995) indicate LASC–G is also infrequent in the Johnston land system.

LASC–H is a major habitat type in the Dryandra and Greenmount land systems and a minor habitat type in the Jaurdi land system.

19 *Eucalyptus ebbanoensis*, *Neurachne annularis* woodland (EENW)

Sampling

5 inventory sites

General information

EENW is described for the first time. It is associated with hills, ridges and footslopes of Bungalbin (Helena and Aurora Range) in the Mount Jackson Plains and Hill Zone in the north-west of the survey area. It occurs on BIF composed of iron-rich bands alternating with red jaspilite bands, as well as on ferruginous rocks and ferricrete. A dense mantle of angular and/or subangular stones and gravels of mixed size, derived from the underlying bedrock is usually present. Soils range from Very shallow soil and Stony soil on the crests of hills and rises, with Stony soil and Shallow loamy gravel on slopes grading to Loamy gravel and Red shallow loam soils on adjacent plains. Ridge crests and ferruginous duricrusts have Bare rock or Stony soil.

Physiognomy and composition of vegetation

EENW occurs as a scattered to close (15–50% PFC) mallee woodland, consisting of scattered (>10–20% PFC), low (<10 m) *Eucalyptus ebbanoensis* subsp. *ebbanoensis* over a variable understorey of dense to scattered grass tussocks of *Neurachne annularis* (Priority 3). The tall and mid shrub strata are also variably developed. On the ridge crests, *Banksia arborea* (Yilgarn dryandra) may be more common than mallees, with dense stands of *Ptilotus obovatus* (cotton bush). On hillslopes, scattered individuals or stands of *Eucalyptus capillosa* (inland wandoo) to 15 m tall may also occur. The low shrub stratum is typically very scattered (>2.5–10% PFC). Variability is influenced by slope, with species richness decreasing on steeper gradients.

The dominant and common species by strata:

Trees and mallees:	Dominant – *Eucalyptus ebbanoensis* subsp. *ebbanoensis* Common – *Banksia arborea* (P4), *Eucalyptus capillosa* Other – *Eucalyptus corrugata*
Tall shrubs:	Dominant – variable; occasionally *Acacia* spp., *Melaleuca* spp. Common – *Acacia quadrimarginea*, *Alyxia buxifolia*, *Calycopeplus paucifolius*, *Eremophila oppositifolia* Others – *Acacia burkittii*, *A. tetragonophylla*, *Allocasuarina acutivalvis* subsp. *acutivalvis*, *Eremophila oldfieldii* subsp. *angustifolia*, *Grevillea obliquistigma**, *Melaleuca hamata*, *M. nematophylla*
Mid shrubs:	Dominant – variable; occasionally *Dodonaea* spp. Others – *Dodonaea inaequifolia*, *Eremophila decipiens**, *Philotheca brucei**, *Senna artemisioides* subsp. *filifolia*, *Westringia cephalantha* var. *cephalantha*
Low shrubs:	Dominant – variable; *Ptilotus obovatus* on ridge crests Common – *Grevillea zygoloba*, *Olearia muelleri*, *Ptilotus obovatus* Others – *Acacia erinacea*, *Olearia pimeleoides*, *Phebalium lepidotum*, *Stenanthemum newbeyi* (P3), *Teucrium disjunctum*
Perennial grasses:	Dominant – *Neurachne annularis* (P3) Other – *Austrostipa elegantissima*
Other plant forms:	Others – *Cassytha nodiflora* (climber), *Cheilanthes lasiophylla* (fern), *Cheiranthera filifolia* (climber), *Dianella revoluta* (perennial herb)

* Also known from Newbey and Hnatiuk (1985)

Priority flora

Bungalbin (Helena and Aurora Range) supports a high number of declared rare and priority species. Some of these are endemic to the range, while others occur on other BIFs. During this survey, *Acacia adinophylla* (Priority 1) and *Banksia arborea* (Priority 4) were recorded at one site, *Neurachne annularis* (Priority 3) at four sites, and *Stenanthemum newbeyi* (Priority 3) at two sites. Other priority species known to be endemic to the range are *Acacia shapelleae* (Threatened), *Lepidosperma bungalbin* (Threatened), *Leucopogon spectabilis* (Threatened) and *Tetratheca aphylla* subsp. *aphylla* (Threatened). Priority species known to be BIF-dependent on the range are *Eremophila hamulata* (Priority 1), *Grevillea georgeana* (Priority 3), *Hibbertia lepidocalyx* subsp. *tuberculata* (Priority 3), *Lepidosperma ferricola* (Priority 3), *Mirbelia ferricola* (Priority 3), *Eucalyptus formanii* (Priority 4) and *Grevillea erectiloba* (Priority 4).

Ecological disturbance

EENW habitat types are associated with the BIF of Bungalbin (Helena and Aurora Range). They are ecologically unique habitats not found in the surrounding landscape. EENW is a major component of the 'Helena and Aurora Range vegetation assemblages (banded iron formation)' which is a Priority Ecological Community with a Priority 1 category (DBCA 2020). The isolation offered by these landforms promotes genetic diversity and vegetation communities have developed significant species endemism and richness. Within the Great Western Woodlands, which encompasses most of the southern Goldfields survey area, Bungalbin is the most significant BIF and the largest and highest topographic feature (704 m above sea level), with the most intact vegetation communities. Communities on other prominent hills and ranges in the southern Goldfields are either considerably altered by grazing (Fraser Range), fire (Jimberlana Hill; Mount Norcott) or are naturally sparse (Kartukartunga – Peak Charles; Wallaroo Rock). The most likely threat comes from future mineral exploration and iron ore mining. Grazing by introduced herbivores is unlikely because EENW is outside the pastoral estate.

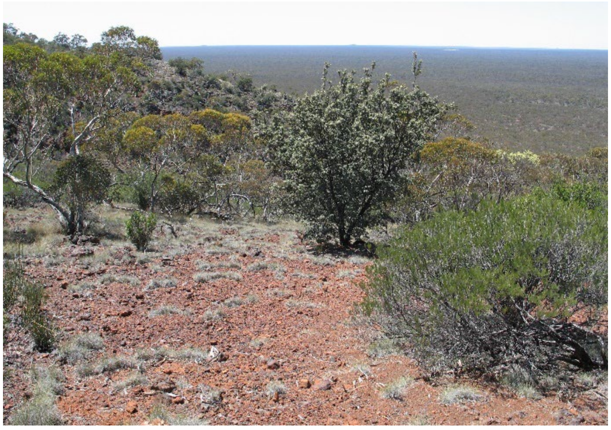
Gradational associations

EENW usually has clearly defined boundaries associated with hills and footslopes, though stands of Inland wandoo woodland (IWWL, #20) can occur within EENW on hillslopes. On footslopes, EENW may abut IWWL or transition into *Neurachne annularis*, eucalypt woodland (NAEW, #21) on adjacent plains.

Land systems

EENW is the dominant habitat type in the Bungalbin and Helena land systems.

Eucalyptus ebbanoensis subsp. *ebbanoensis* woodland with a grass tussock understorey of *Neurachne annularis* on a footslope in the Bungalbin land system



Eucalyptus ebbanoensis subsp. *ebbanoensis* woodland with *Banksia arborea* (Yilgarn dryandra) over *Neurachne annularis* on a hill crest in the Bungalbin land system

Uncommon habitats in Stony plain and low rise non-halophytic shrubland or woodland habitat group

20 Inland wandoo woodland (IWWL)

Sampling

1 inventory site

General information

IWWL is described for the first time but is only provisionally described because there was insufficient sampling. It occurs on the hillslopes, footslopes and adjacent plains associated with Bungalbin (Helena and Aurora Range) in the Mount Jackson Plains and Hill Zone in the north-west of the survey. Soils are Very shallow soil over red–brown hardpan. A dense mantle of fine ironstone gravel lag with scattered stones of BIF and ferricrete forms the surface.

Physiognomy and composition of vegetation

IWWL occurs as a scattered woodland (>10–15% PFC) dominated by *Eucalyptus capillosa* (inland wandoo) to 15 m tall, with very scattered *E. loxophleba* subsp. *lissophloia* (smooth-barked York gum) mallees. *E. ebbanoensis* subsp. *ebbanoensis* may also be occasionally present. Scattered (>10–15% PFC) *Acacia burkittii* (sandhill wattle) is most common through the tall shrub stratum. The mid shrub stratum is sparse. The low shrub stratum may contain isolated individuals or clumps, most often of *Olearia muelleri* (Goldfields daisy) and *Ptilotus obovatus* (cotton bush). Other shrubs occasionally present as isolated individuals include *Acacia quadrimarginea* (granite wattle), *A. tetragonophylla* (curara), *Eremophila alternifolia* (poverty bush), *E. granitica* (thin-leaved poverty bush), *Santalum acuminatum* (quandong), *S. spicatum* (sandalwood) and *Scaevola spinescens* (currant bush). Isolated grass tussocks of *Austrostipa elegantissima* (feather speargrass), *A. scabra* (speargrass) and *Neurachne annularis* (Priority 3) may also be present.

Gradational associations

IWWL may occur as stands within *Eucalyptus ebbanoensis, Neurachne annularis* woodland (EENW, #19) on hillslopes or may transition into EENW where gently inclined footslopes merge with gravelly plains. It may transition into *Neurachne annularis*, eucalypt woodland (NAEW, #21) on the undulating, gravelly plains surrounding Bungalbin (Helena and Aurora Range).

Land systems

IWWL is a minor habitat type in the Bungalbin and Helena land systems.

Scattered woodland dominated by *Eucalyptus capillosa* (inland wandoo) on a red–brown hardpan shallow loam soil in the Helena land system

21 *Neurachne annularis*, eucalypt woodland (NAEW)

Sampling

1 inventory site

General information

NAEW is described for the first time but is only provisionally described because there was insufficient sampling. It is an uncommon habitat with limited distribution, restricted to the Mount Jackson Plains and Hill Zone in the north-west of the survey area. NAEW is associated with footslopes, low rises and gently inclined to gently undulating stony plains around Bungalbin (Helena and Aurora Range). Soils are Loamy gravel overlain by a dense mantle of basalt stones, cobbles and coarse limonite gravel.

Physiognomy and composition of vegetation

NAEW occurs as a very scattered mallee woodland (5–10% PFC) over dense tussocks of *Neurachne annularis* (Priority 3). The tree stratum is dominated by *Eucalyptus loxophleba* subsp. *lissophloia* (smooth-barked York gum), though in some locations *Casuarina pauper* (black oak) is common. The tall and mid shrub stratum is also very scattered (5–10% PFC), with *Acacia burkittii* (sandhill wattle), *A. ramulosa* (horse mulga) and *Melaleuca hamata* present as isolated individuals. The low shrub stratum is sparse, except where juvenile tall shrubs are growing. Other shrubs occasionally present include *Dianella revoluta* (blueberry lily), *Grevillea zygoloba* and *Prostanthera althoferi*.

Gradational associations

NAEW may transition into Inland wandoo woodland (IWWL, #20) on the plains near Bungalbin (Helena and Aurora Range) or Plain York gum, acacia woodland (PYAW, #44) where gravelly, undulating plains transition into adjacent sheetwash plains. NAEW may transition into *Eucalyptus ebbanoensis, Neurachne annularis* woodland (EENW, #19) where plains merge with gently inclined footslopes.

Land systems

NAEW is a major habitat type in the Jackson land system and a minor habitat type in the Bungalbin and Helena land systems.

Grass tussocks of *Neurachne annularis* among scattered *Eucalyptus loxophleba* subsp. *lissophloia* mallees on an undulating plain in the Jackson land system

22 Cotton bush (*Ptilotus*) shrubland (COTS)

Sampling

2 inventory sites

General information

COTS is described for the first time. It is not a common habitat type and occurs predominantly on the slopes of metasedimentary rocks. COTS was observed in 2 locations on the low ridges of metasedimentary rocks associated with the Mount Belches formation (Griffin 1989) north of Lake Randall in the Kambalda Zone. Ridges consist of banded iron and metamorphosed sandstone interbedded with laminated siltstone (Griffin 1989). A variation was also seen on Fraser Range in the Fraser Range Zone on metasedimentary gneisses. Soils are Very shallow stony soil proximal to outcrop, grading downslope into Red shallow loam, overlain with a dense mantle of metasedimentary stones and coarse gravel.

Physiognomy and composition of vegetation

COTS on the Mount Belches formation occurs as a scattered to close (>10–50% PFC) low shrubland, with vegetation coverage dependent on rock outcrop. The low shrub stratum is characterised by the dominance of *Ptilotus obovatus* (cotton bush). Trees are rarely present. *Acacia quadrimarginea* (granite wattle) occurs in the tall shrub stratum but is very scattered (>2.5–10% PFC). Other shrubs occasionally present as isolated individuals include *A. tetragonophylla* (curara), *Maireana* spp. and *Solanum lasiophyllum* (flannel bush). Perennial grasses – such as *Austrostipa scabra* (speargrass), *Cymbopogon ambiguus* (scentgrass), *Enneapogon avenaceus* (bottle washes), *E. caerulescens* (limestone grass) and *Monachather paradoxus* (broad-leaved wanderrie grass) – are common but their abundance varies. COTS on Fraser Range has similarities to Stony dodonaea low shrubland (SDLS, #23).

Gradational associations

COTS is a distinctive habitat type with clearly defined boundaries associated with ridges of metasedimentary rocks. It is usually on slopes between Stony casuarina, bluebush shrubland (SCBS, #30) on ridge crests and Plain eucalypt, bluebush woodland (PEBW, #52) or Calcareous pearl bluebush shrubland (CPBS, #31) on the plains marginal to the footslopes. On Fraser Range COTS may form a mosaic with Stony dodonaea low shrubland (SDLS, #23).

Land systems

COTS is a minor habitat type in the Lawrence and Wyralinu land systems.

Low shrubland of *Ptilotus obovatus* (cotton bush) and mixed perennial grasses on a broad slope associated with a metasedimentary ridge in the Lawrence land system

23 Stony dodonaea low shrubland (SDLS)

Sampling

5 inventory sites, 22 traverse points

General information

SDLS is described for the first time. It is associated with the hills, rises and pediments associated with the Fraser Range Zone in the east of the survey area. Occurring on the Proterozoic rocks forming the Fraser Range, outcrop is common and consists of gabbro, gneiss and metasedimentary rock types. A dense mantle of angular and/or subangular stones and gravels of variable size, derived from the underlying bedrock is usually present. SDLS typically occurs on Very shallow soil with a neutral pH matrix and loamy textures, though the soils can be Red shallow loam or Self-mulching cracking clay in areas of colluvial accumulation or drainage foci within undulating plains.

Physiognomy and composition of vegetation

The presence of bedrock can influence the structure. Frequently occurring as a moderately close (>20–30% PFC) low shrubland, SDLS can also be scattered (>10–15% PFC), particularly on the exposed hill crests. The low shrub stratum is dominated by *Dodonaea* species, mainly *D. adenophora* or *D. microzyga*, though *Ptilotus obovatus* (cotton bush) may be co-dominant. Very scattered (5–10% PFC) *Allocasuarina huegeliana* (rock sheoak) may form the tree stratum, and the tall shrub stratum, if present, is usually only occupied by isolated individuals. The mid shrub stratum is poorly developed and is very scattered to scattered (5–15% PFC). Infrequent clumps of spinifex and/or sedges may be present.

The dominant and common species by strata:

Trees:	Dominant – rarely present as a recognisable stratum; occasionally *Allocasuarina huegeliana* Common – *Pittosporum angustifolium*
Tall shrubs:	Dominant – rarely present as a recognisable stratum
Mid shrubs:	Dominant – variable Common – *Beyeria lechenaultii*, *Pimelea spiculigera* var. *spiculigera*, *Senna artemisioides* Other – *Acacia jennerae*
Low shrubs:	Dominant – *Dodonaea adenophora*, *D. microzyga*; occasionally *Ptilotus obovatus* Common – *Enchylaena tomentosa* (KD), *Ptilotus obovatus* Others – *Scaevola oxyclona*, *Solanum lasiophyllum*, *S. petrophilum*
Perennial grasses:	Dominant – rarely present as a recognisable stratum Others – *Rytidosperma caespitosum* (KD), *Triodia scariosa*
Other plant forms:	Common – *Asphodelus fistulosus* (perennial herb; KI) Others – *Cheilanthes* spp. (fern), *Lepidosperma* spp. (sedge)

Ecological disturbance

SDLS habitats support few palatable perennial species. It is difficult to ascertain the ungrazed state because many areas within Fraser Range are known to have supported large rabbit populations and are historically severely overgrazed. Most SDLS now occurs as moderately close low shrubland dominated by unpalatable *Dodonaea* species, while other areas presumed to have once supported SDLS have been reduced to scattered *Allocasuarina huegeliana* and sparse sedges. The perennial herb *Asphodelus fistulosus* (onion weed) has also colonised some areas, particularly where footslopes and pediments abut degraded valley floors. The grazing history of Fraser Range and the absence of palatable species within SDLS suggest the composition is altered, though it being a natural state is also plausible. Present day grazing is supported by the perennial grass *Rytidosperma caespitosum* (wallaby grass) growing between shrubs and scrub–thickets. Other palatable perennials, such as *Enchylaena tomentosa* (ruby saltbush) and *Ptilotus obovatus*, may indicate improved condition, but since their abundance and occurrence are also influenced by seasonal conditions and spatial variability, absence does not necessarily indicate poor condition. Erosion is limited because of the stony and shallow soil.

Gradational associations

SDLS typically has a distinctive boundary because of the stony soils associated with slopes and pediments, though in some areas it may form a mosaic with Cotton bush (*Ptilotus*) shrubland (COTS, #22). Downslope of the footslopes, SDLS often abuts *Eucalyptus oleosa*, saltbush woodland (EOSW, #56) or *Eucalyptus oleosa*, bindii woodland (EOBW, #57) when adjoining plains, or Speargrass and wallaby grass open grassland (SWOG, #77) or Annual herbland (ANNH, #78) when SDLS is marginal to valley floors.

Land systems

SDLS is a major habitat type in the Gnamma and Wyralinu land systems and a minor habitat type in the Symons land system.

Stony dodonaea low shrubland on a hillslope on Fraser Range in the Wyralinu land system

24 Ridge crest eucalypt woodland (RCEW)

Sampling

1 inventory site, 5 traverse points

General information

RCEW is described for the first time but is only provisionally described because there was insufficient sampling. It occurs in the north of the Fraser Range Zone on low (<10 m) calcrete ridges aligned with west-north-west to east-south-east jointing patterns in the Proterozoic basement rocks. Soils are Very shallow soil over calcrete with loamy texture on Proterozoic rocks. A dense mantle of coarse calcrete gravel is usually present.

Physiognomy and composition of vegetation

RCEW occurs as moderately close (>20–30% PFC) stands of *Eucalyptus griffithsii* (Griffith's grey gum) over a scattered (>15–20% PFC) low shrub understorey of *Atriplex* species. The tall and mid shrub strata are poorly developed, though *Dodonaea lobulata* (bead hopbush), *Geijera linearifolia* (oilbush), *Myoporum platycarpum* (sugarwood) and *Pimelea microcephala* (shrubby riceflower) are occasionally present as isolated individuals. *Rhagodia drummondii* (lake-fringe rhagodia) is common under eucalypts.

Gradational associations

RCEW is usually different from vegetation on surrounding plains because of its association with calcrete ridges and therefore is a distinctive habitat type with clearly defined boundaries. Where mallees encroach down the lower slopes of low ridges, RCEW may merge with Speargrass and Wallaby grass open grassland (SWOG, #77) or Annual herbland (ANNH, #78).

Land systems

RCEW is a minor habitat type in the Yandamurrina land system and is infrequent on other land systems associated with the Fraser Range Zone.

Grove of *Eucalyptus griffithsii* (Griffith's grey gum) over scattered *Atriplex* species on a low calcrete ridge in the Yandamurrina land system

25 Casuarina mixed scrub shrubland (CXSS)

Sampling

2 inventory sites

General information

CXSS was first described in the Nullarbor survey (Waddell et al. 2010), where it is a minor habitat in the Gumbelt and Nyanga land systems in the north-west, commonly on calcrete plains overlain by eolian sand. CXSS is also restricted to the east of the southern Goldfields around the rises and pediments associated with the north-east of Fraser Range. Soils are Red shallow sand over calcrete or Very shallow soil on metasedimentary rocks. The shallow sand appears to be a recent accession over a calcrete bench because the soil matrix is neutral, not alkaline, indicating an origin unrelated to the local regolith.

Physiognomy and composition of vegetation

CXSS contains very scattered (>2.5–10% PFC) *Casuarina pauper* (black oak) trees among a scattered to moderately close (>10–30% PFC) tall shrubland dominated by species of *Acacia*, *Dodonaea* and *Eremophila*. *Eucalyptus oleosa* subsp. *oleosa* (giant mallee), *Myoporum platycarpum* (sugarwood) and *Pittosporum angustifolium* (native willow) are occasionally present. The mid shrub stratum often contains scattered *Dodonaea lobulata* (bead hopbush) over a moderately close low shrub stratum dominated by *Sida calyxhymenia* (tall sida). Other common flora include the mid and low shrubs *Acacia tetragonophylla* (curara), *Eremophila decipiens* (slender fuchsia), *Pimelea microcephala* (shrubby riceflower), *Ptilotus obovatus* (cotton bush), *Scaevola spinescens* (currant bush) and *Solanum lasiophyllum* (flannel bush), and the perennial grass *Eragrostis eriopoda* (woolly butt).

Gradational associations

CXSS transitions into Mallee, hummock grass (spinifex) woodland (MHGW, #35) where soils become increasingly sandier and eucalypts begin to dominate the tree strata and spinifex dominates the understorey.

Land systems

CXSS is a minor habitat type in Nyanga and Yandamurrina land systems.

View across a slight depression between a low metasedimentary ridge and another low ridge supporting a *Casuarina pauper* (black oak) mixed scrub shrubland in the Yandamurrina land system

C Stony plain and low rise chenopod shrubland or woodland habitats

These are upland habitat types containing chenopod shrublands and woodlands with chenopod-dominated understoreys. Chenopod is used in a generic sense to include various low and mid shrubs belonging to the Chenopodiaceae family and associated with often alkaline and saline soils, at least in lower subsoils and sometimes throughout. The most common Chenopodiaceae genera are *Atriplex* (saltbushes) and *Maireana* (bluebushes). The understoreys have similar floristic affinities with chenopod shrublands in lowland, depositional environments.

These habitat types are usually found where erosional processes have only partially removed intensely weathered rock. Shallow soils derived locally from these residuals support these habitat types. Soils are shallow duplexes or red earths, often with a stony mantle of quartz and/or greenstones. They are more common on greenstones but also occur on exposed kaolin-rich saprolite associated with weathered granitic rocks.

Surfaces are more susceptible to accelerated erosion where they are not protected by stone mantles. Erosion susceptibility varies with gradient, whether it has any protective stone or gravel mantle, and the velocity of water shed over the surface. Surfaces that have become bare, mostly due to overgrazing and excessive salinity, can be eroded by wind. Wind winnows the surface material and removes the fine organic matter and clay particles, leaving behind coarser sand and gravel components. Once this has occurred, niches for the recruitment of perennial plants become limited. Cryptogam crusts play a significant role in stabilising the soil surface.

Stony chenopod habitat types are preferentially grazed in favour of the 2 non-halophytic habitat groups A and B. The decline of palatable plant species through grazing pressure reduces understorey cover and results in the fragile soils becoming exposed and susceptible to erosion. Erosion removes the topsoil, which is generally fertile and has low root impedance, leaving behind the dense subsoil that forms an inhospitable substrate for roots of new seedlings. This in turn limits further recruitment of vegetation. Breakaway footslopes are particularly erodible land surfaces, as are some of the alluvial tracts (Kanowna and Woolibar land systems) which drain the greenstone hills. Because of their common association with greenstone landforms, the habitat types of this group are at risk of degradation initiated by mining activities which disturb fragile soil surfaces during construction of infrastructure, such as tracks, drill pads and costeans. Since these habitats consist predominantly of palatable species, they do not regenerate well unless grazing is excluded.

26 Breakaway footslope eucalypt woodland with chenopod understorey (BECW)

Sampling

3 inventory sites, 12 traverse points

General information

BECW was first described in the Sandstone, Yalgoo and Paynes Find area survey (Payne et al. 1998b). It occurs on very gently to gently inclined footslopes and kaolin-rich saprolite adjacent to intensely weathered granitic rocks, which are often capped by ferruginous duricrusts and later exposed at breakaway scarps. Soils are usually shallow saline duplexes over weathered granite, less commonly in contact margins with greenstones, and often have silcrete hardpans in the profile.

Physiognomy and composition of vegetation

BECW usually consists of scattered to moderately close (>10–25% PFC) eucalypt woodland over a low shrubland dominated by Chenopodiaceae, with a poorly developed mid shrub stratum and few tall shrubs or perennial grasses.

The dominant and common species by strata:

Trees:	Dominant – mainly *Eucalyptus salubris* or *E. stricklandii*; occasionally *E. transcontinentalis*
	Common – *Casuarina pauper*, *Eucalyptus lesouefii*
	Others – *Eucalyptus cylindrocarpa* (mallee), *E. loxophleba* subsp. *lissophloia*
Tall shrubs:	Dominant – rarely present as a recognisable stratum
	Others – *Acacia quadrimarginea*, *A. tetragonophylla*, *A. ramulosa* var. *ramulosa*, *Alyxia buxifolia*, *Eremophila alternifolia*, *E. oppositifolia*, *Exocarpos aphyllus*, *Melaleuca hamata*, *Santalum spicatum*
Mid shrubs:	Dominant – variable
	Common – *Acacia erinacea*, *Atriplex nummularia* subsp. *spathulata*, *Dodonaea lobulata*, *Scaevola spinescens*
	Others – *Cratystylis conocephala*, *Eremophila scoparia*
Low shrubs:	Dominant – *Atriplex bunburyana* (KD), *A. vesicaria* (KD)
	Common – *Enchylaena tomentosa* (KD), *Maireana tomentosa*, *M. triptera*, *Ptilotus obovatus*, *Rhagodia drummondii* (KD), *Scaevola spinescens*
	Others – *Atriplex stipitata* (KI), *Frankenia* spp., *Maireana sedifolia*
Perennial grasses:	Dominant – not present as a recognisable stratum
	Others – *Austrostipa elegantissima*, *A. scabra*
Other plant forms:	Common – *Sclerolaena diacantha* (perennial herb)

Ecological disturbance

BECW is a favoured habitat for livestock, goats and kangaroos because of the palatable and accessible flora, as well as the presence of ephemeral freshwater pools and rock shelters along the scarps among breakaway duricrust. Under excessive grazing pressure, many of the more common low shrubs – such as *Atriplex bunburyana* (silver saltbush), *A. vesicaria* (bladder saltbush), *Enchylaena tomentosa* (ruby saltbush) and *Rhagodia* spp. – are removed. *Ptilotus obovatus* (cotton bush) may then increase but can also be removed through ongoing grazing pressure. *Atriplex stipitata* (kidney saltbush) is not generally grazed and can succeed palatable species as the dominant understorey shrub. However, its dominance may also be natural (Mitchell and Wilcox 1994). Kaolinised surfaces and duplex soils are extremely fragile and highly erodible. Placement of infrastructure along the bases of breakaways should be avoided.

Gradational associations

BECW usually occurs as a distinctive habitat type with clearly defined boundaries, but as chenopods are replaced by taller, non-halophytic species, it may transition downslope into Plain eucalypt (mallee), acacia woodland (PEAW, #43) in the centre and eastwards or Plain York gum, acacia woodland (PYAW, #44) in the west. Where footslopes level into plains and chenopods remain prominent, BECW transitions into habitat types common to group J: Depositional plain mixed halophyte shrubland habitats.

Land systems

BECW is a major habitat type in the Cundlegum and Euchre land systems and a minor habitat type in the Gransal, Illaara, Kurrawang, Latimore and Monger land systems.

Gently inclined breakaway footslope on kaolin-rich saprolite supporting an open *Eucalyptus salubris* (gimlet) woodland over *Atriplex vesicaria* (bladder saltbush)

27 Greenstone eucalypt, bluebush woodland (GEBW)

Sampling

6 inventory sites, 39 traverse points

General information

GEBW is described for the first time. It occurs on gently inclined footslopes of the greenstone hills and low rises as well as lower slopes of metasedimentary ridges in the greenstone-dominated Kambalda Zone. GEBW is typically characterised by Calcareous very shallow soil and Calcareous stony soil, though colluvial accumulation on lower slopes results in Calcareous shallow loam soil developing. The mantle usually consists of a moderate to abundant quantity of angular, angular-platy or subangular stones and cobbles derived from upslope scree and the underlying bedrock. The accumulation of calcium carbonate as soft, fine material within the soil matrix becomes accentuated over time and calcrete pans often develop within the soil profile.

Physiognomy and composition of vegetation

GEBW occurs as a very scattered to scattered (>2.5–20% PFC), low (<10 m) eucalypt woodland with a very scattered to moderately close (5–25% PFC) mid to low shrubland dominated by *Maireana sedifolia* (pearl bluebush). The tree stratum is typically dominated by *Eucalyptus griffithsii* (Griffith's grey gum), though *E. lesouefii* (Goldfields blackbutt) occasionally dominates. The tall shrub stratum is variably developed. Perennial grasses are patchily distributed.

The following species are dominant and/or common:

Trees:	Dominant – stratum rarely dominant; occasionally *Eucalyptus lesouefii* Common – *Casuarina pauper* Others – *Eucalyptus salmonophloia*, *E. transcontinentalis*
Mallees:	Dominant – *Eucalyptus griffithsii* Others – *Eucalyptus gracilis*, *E. oleosa* subsp. *oleosa*
Tall shrubs:	Dominant – variable; often *Acacia* spp., *Dodonaea* spp. or *Eremophila* spp.

	Common – *Acacia tetragonophylla*, *Dodonaea lobulata* (KI)
	Others – *Acacia burkittii*, *Eremophila oppositifolia*, *Santalum spicatum*
Mid shrubs:	Dominant – *Maireana sedifolia*; occasionally *Dodonaea lobulata* (KI)
	Common – *Eremophila glabra* (KD), *Senna artemisioides* subsp. *filifolia* (KI)
	Others – *Atriplex nummularia* subsp. *spathulata*, *Sida calyxhymenia* (KD)
Low shrubs:	Dominant – *Maireana sedifolia*; occasionally co-dominant with *Ptilotus obovatus*
	Common – *Enchylaena tomentosa* (KD), *Olearia muelleri*, *Ptilotus obovatus*, *Scaevola spinescens*, *Solanum lasiophyllum*
	Others – *Atriplex vesicaria* (KD), *Maireana tomentosa*, *M. triptera*
Perennial grasses:	Dominant – rarely present as a recognisable stratum
	Common – *Austrostipa scabra*, *Enneapogon caerulescens, Paspalidium constrictum*
	Other – *Austrostipa elegantissima*
Other plant forms:	Common – *Sclerolaena diacantha* (perennial herb)

Ecological disturbance

Palatable species – such as *Atriplex vesicaria* (bladder saltbush), *Enchylaena tomentosa* (ruby saltbush), *Eremophila glabra* (tar bush), *Ptilotus obovatus* (cotton bush), *Scaevola spinescens* (currant bush) and *Sida calyxhymenia* (tall sida) – are likely to be reduced by excessive grazing pressure. Unpalatable species, such as *Dodonaea lobulata* (bead hopbush) and *Senna artemisioides* subsp. *filifolia* (desert cassia), may increase in abundance in response to overgrazing. Dense stone mantles provide some stability to the surface and protect against erosion, but mantles of lesser density provide little protection from heavy rain that results in surface run-off. This difference is amply demonstrated by comparing the highly erodible surface of the Woolibar land system to the less erodible and stonier Kanowna land system. GEBW is likely to respond to disturbance events in a similar manner to Stony casuarina, bluebush shrubland (SCBS, #30) and Plain eucalypt, bluebush woodland (PEBW, #52).

Scattered eucalypt woodland over a *Maireana sedifolia* (pearl bluebush) shrubland on a hillslope associated with a quartz ridge in the Lawrence land system

Gradational associations

As gradients lessen towards plains, the soil depth increases and GEBW commonly transitions into PEBW, with *Eucalyptus salmonophloia* (salmon gum) replacing *E. griffithsii*, or changes into Calcareous pearl bluebush shrubland (CPBS, #31) if eucalypts are absent. Where resistant rock types form low rises within erodible plains, such as in the Kanowna and Woolibar land systems, GEBW may transition into Plain eucalypt, halophytic woodland (PEHW, #60) on lower slopes where subsoil salinity increases and *Tecticornia* species (samphire) replace *Maireana sedifolia*.

Land systems

GEBW is a major habitat type in the Lawrence land system and minor habitat type in the Coolgardie, Woolibar and Zed land systems. GEBW features in many land systems within the Kambalda Zone, often at ecotone boundaries where gradients change and the vegetation transitions into adjacent habitat types.

28 Greenstone eucalypt, saltbush woodland (GESW)

Sampling

12 inventory sites, 159 traverse points

General information

GESW is described for the first time. It occurs on gently to very gently inclined lower slopes and footslopes of the greenstone hills and low rises in the greenstone-dominated Kambalda Zone. GESW is characterised by Calcareous shallow loam and Calcareous gravelly shallow loam on the upper footslopes and Calcareous loamy earth, Calcareous clay loam and Alkaline red shallow loamy duplex on the lower footslopes. A dense mantle of stones and gravels of variable shape and size is frequently present. Most often, the mantle consists of metabasalt, but other rock types derived from upslope scree or the underlying bedrock may also be present.

On some hills, GESW is intermediary between Greenstone hill eucalypt woodland (GHEW, #2) on the upper hillslopes and Plain eucalypt, saltbush woodland (PESW, #58) on the adjacent plains below. Geology, soil type and depth, stone content and gradient are the primary properties differentiating these 3 habitat types. These differences cause variation in water availability for the extant vegetation, which in turns affects the dominant eucalypts present and the density of saltbush understorey.

Mixed eucalypt woodland over an *Atriplex*-dominated understorey on a hill in the Coolgardie land system

Physiognomy and composition of vegetation

GESW occurs as a scattered to moderately close (15–50% PFC) eucalypt woodland over a very scattered to scattered (5–15% PFC) mid to low shrubland dominated by *Atriplex* species: *A. nummularia* subsp. *spathulata* (old man saltbush) is most common in the mid shrub stratum and *A. vesicaria* (bladder saltbush) is most common in the low shrub stratum. The tree stratum is frequently dominated by *Eucalyptus lesouefii* (Goldfields blackbutt), though variation in geology, topography and regional distribution also results in occasional co-dominance with a variety of other eucalypts, such as *E. campaspe* (silver gimlet), *E. griffithsii* (Griffith's grey gum) or *E. torquata* (coral gum) nearer to hill or rise crests, and *E. salmonophloia* (salmon gum) marginal to plains and valley floors. The tall shrub stratum is variable, with species and foliar cover often influenced by grazing intensity. Eremophilas frequently dominate the tall, and occasionally mid, shrub strata. In some locations *Eremophila scoparia* (broom bush) may be co-dominant with, or replace, *A. nummularia* subsp. *spathulata*. Perennial grasses are sparse.

The dominant and common species by strata:

Trees:	Dominant – *Eucalyptus lesouefii*; occasionally *E. campaspe*, *E. salmonophloia* (lower footslopes), *E. torquata* Other – *Casuarina pauper*
Mallees:	Dominant – *Eucalyptus griffithsii* Others – *Eucalyptus celastroides* subsp. *celastroides*, *E. oleosa* subsp. *oleosa*
Tall shrubs:	Dominant – various *Eremophila* spp.; often *E. interstans* subsp. *interstans* (KI); occasionally *E. oppositifolia, E. scoparia* (KI) Common – *Dodonaea lobulata*, *Eremophila interstans* subsp. *interstans* (KI), *E. oppositifolia*, *E. scoparia* (KI), *Exocarpos aphyllus* Other – *Santalum acuminatum*
Mid shrubs:	Dominant – *Atriplex nummularia* subsp. *spathulata*; occasionally *Eremophila scoparia* (KI) Common – *Eremophila scoparia* (KI), *Senna artemisioides* subsp. *filifolia* (KI) Others – *Eremophila decipiens* (KI), *E. glabra* (KD), *Maireana sedifolia*
Low shrubs:	Dominant – *Atriplex vesicaria* (KD); occasionally *Atriplex bunburyana* (KD), *Ptilotus obovatus* Common – *Acacia erinacea*, *Enchylaena tomentosa* (KD), *Eremophila parvifolia* subsp. *auricampa* (KD), *Maireana tomentosa*, *M. triptera*, *Olearia muelleri*, *Ptilotus obovatus*, *Scaevola spinescens* Others – *Maireana pentatropis*, *M. radiata*, *Solanum lasiophyllum*
Perennial grasses:	Dominant – rarely present as a recognisable stratum Common – *Austrostipa scabra* Other – *Austrostipa elegantissima* (KD)
Other plant forms:	Common – *Sclerolaena diacantha* (perennial herb)

Ecological disturbance

Since the understorey is similar to Plain eucalypt, saltbush woodland (PESW), responses to disturbance are also comparable, with the density and composition of palatable understorey shrubs providing the most reliable indicator of condition and grazing impacts. An abundance of palatable species indicates low grazing pressure, while their absence indicates past or present overgrazing or fire. The absence of *P. obovatus*, which is influenced by seasonal conditions that make its abundance naturally variable, does not necessarily indicate poor condition. The common occurrence of an extensive stony mantle usually offers effective protection against erosion unless surface disturbance is significant, as occurs with track and drill pad construction.

Gradational associations

As part of a topographic catena sequence, GESW may occur intermediate between Greenstone hill eucalypt woodland (GHEW, #2) and Plain eucalypt, saltbush woodland (PESW, #58). With decreasing soil depth and stonier soils on upper hillslopes and *Atriplex* species diminishing in prominence, GESW can merge upslope into GHEW or Eucalypt blackbutt grove or stand (EBBG, #17) on rise crests. With increasing soil depth as footslopes merge with valley floors, GESW often transitions downslope into PESW or Plain eucalypt, halophytic woodland (PEHW, #60), where soil salinity increases. GESW may abut *Eucalyptus ravida*, halophytic woodland (ERHW, #29) where saline drainage tracts border upland interfluves.

Land systems

GESW is a major habitat type in the Coolgardie land system and a minor habitat type in the Dunnsville, Graves, Illaara, Jaurdi, Kanowna, Monger and Moriarty land systems.

29 *Eucalyptus ravida,* halophytic woodland (ERHW)

Sampling

6 inventory sites, 7 traverse points

General information

ERHW is described for the first time. It is typically associated with moderately inclined to gently undulating gritty-surfaced stony plains derived from granitoid uplands and the level, sluggish, saline drainage tracts which meander between the interfluves of these uplands. Soils are typically derived from deeply weathered granite and consist of Red–brown non-cracking clay with saline subsoil or Saline clay soil, both of which are gypsiferous at depth. A moderate mantle of coarse (2–6 cm), subangular quartz gravels commonly forms the surface.

ERHW is similar to Plain eucalypt, halophytic woodland (PEHW, #60) but is considered a different habitat type because of its upland location, the dominance of *Eucalyptus ravida* in the tree stratum, and the co-dominant, scattered occurrence of *Atriplex vesicaria* (bladder saltbush) and species of *Frankenia* and *Tecticornia* (samphire) in the low shrub stratum.

Physiognomy and composition of vegetation

ERHW occurs as a scattered (>10–20% PFC) eucalypt woodland dominated by *Eucalyptus ravida* over a scattered (>10–15% PFC) low shrubland co-dominated by *Atriplex vesicaria*, *Frankenia* and *Tecticornia* species. Tall and mid shrub species usually occur within tree-based clumps among the eucalypts or as isolated individuals. Perennial grasses are rarely present.

The dominant and common species by strata:

Trees and mallees:	Dominant – *Eucalyptus ravida*; occasionally co-dominant with *E. campaspe*, *E. lesouefii*, *E. salmonophloia* or *E. salubris* Common – *Eucalyptus salmonophloia* (when other species are dominant) Others – *Eucalyptus celastroides*, *E. celastroides* subsp. *celastroides*
Tall shrubs:	Dominant – rarely present as a recognisable stratum Common – *Eremophila interstans* subsp. *interstans* (KI), *E. interstans* subsp. *virgata* (KI), *E. scoparia* (KI), *Exocarpos aphyllus*, *Pittosporum angustifolium*, *Santalum acuminatum*
Mid shrubs:	Dominant – rarely present as a recognisable stratum Common – *Atriplex nummularia* subsp. *spathulata*, *Cratystylis conocephala*, *Eremophila glabra* (KD), *E. ionantha*, *E. scoparia* (KI), *Senna artemisioides* subsp. *filifolia* Other – *Maireana sedifolia*
Low shrubs:	Dominant – *Atriplex vesicaria* (KD), *Frankenia tetrapetala*, *Tecticornia disarticulata*; occasionally *T. halocnemoides* Common – *Enchylaena tomentosa* (KD), *Lycium australe*, *Maireana tomentosa*, *M. triptera*, *Olearia muelleri*, *Ptilotus obovatus*, *Rhagodia drummondii* (KD), *Scaevola spinescens* Other – *Tecticornia doliiformis*
Other plant forms:	Common – *Maireana trichoptera* (perennial herb), *Sclerolaena diacantha* (perennial herb) Other – *Carpobrotus* spp. (succulent perennial herb)

Ecological disturbance

ERHW is likely to show similar response to disturbances as Plain eucalypt, halophytic woodland (PEHW, #60). Drainage foci and gilgais can be invaded by *Eremophila interstans* subsp. *virgata* when the habitat type is in poor condition.

Gradational associations

Where saline drainage tracts flow through habitat types dominated by halophytic understoreys, ERHW may transition subtly into adjacent habitat types, such as Greenstone eucalypt, saltbush woodland (GESW, #28), Plain eucalypt, saltbush woodland (PESW, #58) and Plain eucalypt, halophytic woodland (PEHW, #60). Elsewhere, boundaries are usually clearly defined.

Halophytic shrubs in a saline drainage tract which meanders through mixed eucalypt woodland dominated by *Eucalyptus campaspe* (silver gimlet) and *E. ravida* in the Dunnsville land system

Land systems

ERHW is a major habitat type in the Dunnsville land system and minor habitat type in the Kanowna land system.

30 Stony casuarina, bluebush shrubland (SCBS)

Sampling

7 inventory sites, 36 traverse points

General information

SCBS is described for the first time. It is associated with footslopes of the metasedimentary ridges and low rises scattered throughout the survey area, and is similar to Casuarina ridge woodland (CRIW, #5). It occurs on the crests of low rises, or as part of a topographic catena sequence with CRIW on the crests and upper slopes of ridges on bare rock, and SCBS on the lower slopes. Soils grade from Stony soil on ridge crests to Calcareous very shallow soil on upper slopes to Very shallow soil over calcrete and Calcareous gravelly shallow loam on lower slopes as colluvium accumulates. A dense mantle of angular to subangular stones and coarse gravels derived from upslope scree and the underlying bedrock usually forms the surface.

Physiognomy and composition of vegetation

SCBS consists of very scattered (>2.5–10% PFC) *Casuarina pauper* (black oak) trees, occasionally in groves or stands, among a scattered to moderately close (>10–25% PFC) shrubland. The tall and mid shrub strata are variably developed. The low shrub stratum, while generally very scattered (5–10% PFC), is characterised by *Maireana sedifolia* (pearl bluebush).

The dominant and common species by strata:

Trees:	Dominant – *Casuarina pauper* Common – *Acacia aneura* Other – *Eucalyptus griffithsii* (mallee)
Tall shrubs:	Dominant – variable; often *Acacia* spp. or *Eremophila* spp. Common – *Acacia aneura*, *A. quadrimarginea*, *A. tetragonophylla*, *Eremophila alternifolia* Others – *Acacia burkittii*, *Eremophila oppositifolia*
Mid shrubs:	Dominant – *Dodonaea lobulata* (KI) Common – *Senna artemisioides* subsp. *filifolia* (KI), *Sida calyxhymenia* (KD) Others – *Atriplex nummularia* subsp. *spathulata*, *Eremophila decipiens*, *E. glabra*, *E. granitica*
Low shrubs:	Dominant – *Maireana sedifolia* Common – *Atriplex vesicaria* (KD), *Enchylaena tomentosa* (KD), *Lycium australe*, *Maireana triptera*, *Ptilotus obovatus*, *Scaevola spinescens* (KD), *Solanum lasiophyllum*
Perennial grasses:	Dominant – rarely present as a recognisable stratum Common – *Enneapogon caerulescens*
Other plant forms:	Common – *Leichhardtia australis* (climber)

Ecological disturbance

Disturbance events affecting Casuarina ridge woodland (CRIW, #5) and Calcareous pearl bluebush shrubland (CPBS, #31) are likely to have similar effects on SCBS. Palatable species – such as *Atriplex vesicaria* (bladder saltbush), *Enchylaena tomentosa* (ruby saltbush), *Ptilotus obovatus* (cotton bush), *Sida calyxhymenia* (tall sida) and *Scaevola spinescens* (currant bush) – may decrease with grazing, with unpalatable species, such as *Dodonaea lobulata* (bead hopbush) and *Senna artemisioides* subsp. *filifolia* (desert cassia), increasing in abundance. Stone mantles provide some stability and protection against erosion.

Gradational associations

As part of a topographic catena sequence, SCBS may occur intermediate between CRIW and CPBS. With increasing bare rock towards ridge crests and *Maireana sedifolia* diminishing in prominence, SCBS can transition upslope into CRIW. Along the footslopes, SCBS often transitions downslope into CPBS as soils deepen and become less stony.

Land systems

SCBS is a major habitat type in the Lawrence land system and a minor habitat type in the Gundockerta, Kanowna, Kurrawang and Zed land systems.

Maireana sedifolia (pearl bluebush) shrubland with very scattered *Casuarina pauper* (black oak) on the slopes of a metasedimentary ridge in the Lawrence land system

31 Calcareous pearl bluebush shrubland (CPBS)

Sampling

30 inventory sites, 605 traverse points

General information

CPBS is described in the north-eastern Goldfields survey (Pringle et al. 1994) and is similar to Pearl bluebush low shrubland (PBLS) in the WA Nullarbor survey (Waddell et al. 2010). It is characterised by *Maireana sedifolia*-dominated low shrublands. CPBS occurs on the undulating stony plains associated with predominantly greenstone environments. The dominant features are a calcareous soil matrix, often with calcareous concretions and calcrete pans. As such, Calcareous stony soil and Very shallow soil over calcrete occupy the rises of plains, and Calcareous gravelly shallow loam and Calcareous shallow loam soils occupy areas near rises. Occasionally, rises have ironstone gravel soil that has been overprinted with calcareous materials, forming Shallow calcrete ironstone gravel soil. Lower slopes have Calcareous loamy earth (sometimes gravelly) and Alkaline red shallow loamy duplex soils. In broad, sluggish drainage tracts, CPBS is associated with heavy-textured clay soils, often calcareous. These most often take the form of Self-mulching cracking clay soils, but Hard cracking clay soil sometimes occurs. The presence and density of a stony mantle varies.

Physiognomy and composition of vegetation

CPBS consists of scattered (>10–20% PFC), occasionally moderately close (>20–30% PFC), shrublands with *Maireana sedifolia* (pearl bluebush) dominating the low and mid shrub strata. Tall shrubs and trees are typically very scattered, with *Casuarina pauper* (black oak) common. When in good condition, *Atriplex vesicaria* (bladder saltbush) is co-dominant with *M. sedifolia*.

The dominant and common species by strata:

Trees:	Dominant – rarely present other than as emergents; occasionally, very scattered *Casuarina pauper*
	Common – *Acacia aneura* (in the north), *Casuarina pauper*, *Pittosporum angustifolium*
	Others – *Eucalyptus salmonophloia*, *E. salubris* (in the south)
Tall shrubs:	Dominant – rarely present other than as emergents
	Common – *Acacia aneura* (in the north), *A. burkittii*, *A. tetragonophylla*, *Eremophila alternifolia*, *E. oldfieldii*, *E. oldfieldii* subsp. *angustifolia*
	Others – *Acacia hemiteles*, *Alectryon oleifolius*, *Eremophila oppositifolia*, *Exocarpos aphyllus*, *Hakea preissii* (KI), *Santalum spicatum*
Mid shrubs:	Dominant – *Maireana sedifolia*
	Common – *Atriplex nummularia* subsp. *spathulata*, *Dodonaea lobulata* (KI), *Eremophila glabra*, *E. scoparia*, *Senna artemisioides* subsp. *filifolia* (KI), *Sida calyxhymenia* (KD)
	Others – *Cratystylis subspinescens* (KD), *Eremophila decipiens*
Low shrubs:	Dominant – *Atriplex vesicaria* (KD), *Maireana sedifolia*, *Ptilotus obovatus*
	Common – *Enchylaena tomentosa* (KD), *Maireana georgei* (KD), *M. pyramidata*, *M. tomentosa*, *M. triptera*, *Olearia muelleri*, *Rhagodia drummondii* (KD), *Scaevola spinescens*, *Solanum lasiophyllum*
	Other – *Lycium australe*
Perennial grasses:	Dominant – rarely present as a recognisable stratum
	Common – *Austrostipa elegantissima*, *A. scabra, Enneapogon caerulescens*
	Others – *Enteropogon ramosus*, *Eragrostis setifolia*, *Rytidosperma caespitosum*
Other plant forms:	Common – *Leichhardtia australis* (climber), *Sclerolaena diacantha* (perennial herb), *S. obliquicuspis* (perennial herb)
	Other – *Sida spodochroma* (perennial herb)

Ecological disturbance

While livestock have been observed eating *Maireana sedifolia,* it is primarily only the plant tips, particularly new shoots. As the leaves contain up to 10% salt (Mitchell and Wilcox 1994), their palatability is influenced by the availability of fresh water. Therefore, *M. sedifolia* is not a sensitive indicator of rangeland condition in the southern Goldfields. In good condition this habitat type varies from conspicuous stands of *Atriplex vesicaria* with *Maireana georgei* (George's bluebush) to a few plants of *Ptilotus obovatus* (cotton bush), with good diversity of palatable perennial shrubs – such as *Enchylaena tomentosa* (ruby saltbush), *Sclerolaena diacantha* (grey bindii) – and palatable grasses, such as *Austrostipa elegantissima* (feather speargrass), *Enneapogon caerulescens* (limestone grass) and *Rytidosperma caespitosum* (wallaby grass). Traverses out from water points concur with the observations of Pringle et al.

(1994) that on relatively uniform CPBS, the most sensitive measure of grazing impact is the composition and density of palatable shrubs distributed between *M. sedifolia* plants. In fair condition, CPBS can be reduced to a monospecific stand of *M. sedifolia* as the abundance of palatable species decreases and is replaced by less palatable, seasonally dependent facultative perennials – such as *Sclerolaena obliquicuspis* (limestone bindii) and *S. patenticuspis* (spear-fruit copperburr) – or with *Austrostipa scabra* (speargrass) encroaching between the bluebush mounds. In poor condition, CPBS can become invaded by unpalatable shrubs – like *Hakea preissii* (needle bush) and *Senna artemisioides* subsp. *filifolia* (desert cassia) – and annuals, such as *Carrichtera annua* (Ward's weed) and *Salsola australis* (roly poly).

Maireana sedifolia is a long-lived species that does not establish readily. Its ability to cope with arid conditions and regenerate from low intensity fires has allowed it to become a dominant species in these habitats, although it can be eliminated by intense or frequent fires (Mitchell et al. 1979). While *M. sedifolia* can tolerate a low intensity burn, *Atriplex vesicaria* is sensitive to fire and rarely survives any fire (Fitzgerald 1976; Graetz and Wilson 1984). Regeneration after fire by *Atriplex* spp. is by seed alone. If grazing pressure inhibits recovery after fire, there is risk of completely diminishing the seed bank (Hodgkinson and Griffin 1982). Some monospecific stands of *M. sedifolia* in CPBS may indicate areas that had inadequate protection from grazing during a recovery phase after fire, or have been excessively overgrazed, and have subsequently lost their *Atriplex* spp. component through exhaustion of the seedbank.

Maireana sedifolia (pearl bluebush) dominated shrubland on the Gundockerta land system

Soils in healthy CPBS communities have well-developed cryptogamic crusts of algae, lichens and liverworts, which improve nutrient cycling, soil moisture retention, and provide protection against raindrop impact, sheet flow and wind erosion. The loss of cryptogamic crust reduces soil stability and can indicate declining condition. Where the cryptogamic crust is broken, erosion often ensues. This is most commonly observed on gentle slopes, which are extremely susceptible to water erosion that can be aggravated by infrastructure location.

Pearl bluebush shrubland on a very gently inclined plain with gully erosion caused by a track orientated parallel to water sheet flow which is shed off the rise in the background

Gradational associations

In greenstone-dominated landscapes, CPBS transitions downslope from low rises into adjacent valley floors and sluggish drainage tracts which support Bladder saltbush low shrubland (BLSS, #72), Plain mixed halophyte shrubland (PXHS, #70) or Plain sago bush shrubland (PSAS, #73). Along the footslopes of adjacent greenstone hills or metasedimentary ridges, CPBS often transitions upslope into either Stony casuarina, bluebush shrubland (SCBS, #30) or Casuarina ridge woodland (CRIW, #5) as *Casuarina pauper* (black oak) becomes more prominent. Elsewhere, on the plains between the rises and drainage foci, CPBS transitions into Plain eucalypt, bluebush woodland (PEBW, #52) as eucalypts become more common.

Where undulating plains grade into alluvial plains adjacent to lake country CPBS transitions into Calcareous casuarina, acacia shrubland or woodland (CCAS, #80) as *Casuarina pauper* and acacias become more conspicuous in the overstorey. In lake country on calcrete platforms, there is usually a distinct boundary between the pearl bluebush-dominated shrublands of CPBS and the more diverse halophytic communities of PXHS.

Land systems

CPBS is a major habitat type in the Bunyip, Deadman, Gundockerta, Lawrence, Moorebar and Woolibar land systems and a minor habitat type in the Carnegie, Graves, Kanowna and Moriarty land systems.

32 Stony plain bluebush mixed shrubland (SBMS)

3 inventory sites, 5 traverse points

General information

SBMS is described in the north-eastern Goldfields (Pringle et al. 1994) and Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b) surveys where it is widely distributed. In the southern Goldfields, SBMS occurs infrequently and is restricted to the central north of the survey area. It occurs on erosional surfaces associated with very gently inclined saline stony plains and footslopes on either weathered granite or, less frequently, below greenstone hills. Soils are generally red duplex types – Alkaline red shallow sandy duplex and Very shallow soil over (silcrete or red–brown) hardpan – covered by stony mantles, consisting mostly of quartz.

Saline stony plain supporting a chenopod-dominated low shrubland on the Gundockerta land system

Physiognomy and composition of vegetation

SBMS consists of very scattered to scattered (5–20% PFC), occasionally moderately close (>20–25% PFC), low shrublands dominated by species of *Maireana* (bluebushes). The tall and mid shrub strata are less developed, and trees are rare. Perennial grasses are typically absent.

The dominant and common species by strata:

Trees:	Dominant – rarely present other than as emergents Other – *Casuarina pauper*
Tall shrubs:	Dominant – rarely present other than as emergents Others – *Acacia tetragonophylla*, *Exocarpos aphyllus*, *Hakea preissii* (KI)
Mid shrubs:	Dominant – occasionally *Cratystylis subspinescens* (KD) Common – *Cratystylis subspinescens* (KD), *Eremophila scoparia* (KI), *Senna artemisioides* subsp. *filifolia* (KI) Others – *Atriplex nummularia* subsp. *spathulata*, *Eremophila decipiens*
Low shrubs:	Dominant – various *Maireana* spp., including *M. glomerifolia* (KD), *M. platycarpa* (KD), *M. pyramidata* Common – *Atriplex vesicaria* (KD), *Frankenia* spp., *Maireana georgei* (KD), *M. glomerifolia* (KD), *M. platycarpa* (KD), *M. pyramidata*, *M. tomentosa*, *M. triptera* Others – *Enchylaena tomentosa* (KD), *Ptilotus obovatus*, *Scaevola spinescens*, *Solanum lasiophyllum*
Other plant forms:	Common – *Leichhardtia australis* (climber), *Sclerolaena diacantha* (perennial herb) Other – *Sclerolaena drummondii* (perennial herb)

Ecological disturbance

SBMS habitats were insufficiently sampled during this survey. However, information from Pringle et al. (1994), Burnside et al. (1995) and Payne et al. (1998b) indicate SBMS is very susceptible to overgrazing. This leads to a decrease in palatable species, such as *Maireana georgei* (George's bluebush), *M. glomerifolia* (ball leaf bluebush), *M. platycarpa* (shy bluebush), *Ptilotus obovatus* (cotton bush) and *Sclerolaena diacantha* (grey bindii). The loss of palatable shrubs is typically accompanied with an increase in unpalatable species, such as *Hakea preissii* (needle bush) and to a lesser extent *Senna artemisioides* subsp. *filifolia* (desert cassia). However, this increase rarely matches the general reduction in shrub cover, which leaves the soil susceptible to accelerated erosion. Payne et al. (1998b) observed that when shrub foliar cover in SBMS decreases to below 10%, erosion appears to become more frequent and extensive.

Gradational associations

Upslope of SBMS, the boundary is usually distinctive because of its shallower and stonier soils. As alluvial processes become more influential and the soil depth increases and the stone mantle dissipates, SBMS often transitions downslope into Plain mixed halophyte shrubland (PXHS, #70) or Plain sago bush shrubland (PSAS, #73).

Land systems

SBMS is a minor habitat type in the Gransal, Gundockerta and Moriarty land systems.

D Sandplain hummock grassland habitats

This group is characterised by sandplains and sand sheets supporting hummock grasslands, typically dominated by *Triodia* spp. (spinifex). In adjacent rangeland surveys to the north (Pringle et al. 1994; Payne et al. 1998b), subtypes within this group were distinguished by the floristics of the most prominent stratum subordinate to the hummock grass stratum. In these northern surveys, Sandplain spinifex hummock grassland (SASP, #33) was treated as the major habitat type, with other component types used to provide more information in the field about strata other than the spinifex layer. Some of these habitat types, such as Sandplain mallee, spinifex woodland (SAMA, #34), are now treated as distinct because of their prominence in the southern Goldfields.

While many sandplain hummock grasslands occur on Red deep sands, 2 habitat types differ because of edaphic factors. SAMU, which occurs as distinct mulga patches surrounded by a matrix of spinifex grassland, occurs on Sandy earth or Loamy earth soils which tend to be shallow because of hardpan development. Mallee, hummock grass (spinifex) woodland (MHGW, #35) occurs on shallow eolian sand sheets over calcareous plains which contain calcrete concretions within the soil profile.

While spinifex grasses dominate many sandplains elsewhere in WA's arid zone, they are largely restricted to the north of this survey in sandplains associated with the Murchison and Great Victoria Desert provinces and the Bimbijy Sandplains Zone in the north-west of the Kalgoorlie Province.

These habitats have very low pastoral value, primarily because of the low palatability of spinifex.

33 Sandplain spinifex hummock grassland (SASP)

Sampling

4 inventory sites, 7 traverse points

General information

SASP and equivalent sandplain habitat types are described in the Murchison River catchment (Curry et al. 1994), north-eastern Goldfields (Pringle et al. 1994) and the Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b) surveys. They dominate the arid interior of WA beyond the pastoral zone and are characteristic of the Eremaean Botanical Province (Beard 1990) and Great Victoria Desert bioregion (Environment Australia 2000). SASP is associated with extensive sandplains and occasional dunefields in the north and north-east of the southern Goldfields. Sandplain soils are commonly Red or Yellow sandy earths, and occasionally Red loamy earths. In the survey area, the dune soils are most commonly Yellow deep sands and sometimes Red deep sands, both derived from siliceous, unconsolidated parent material.

Vegetation is significantly influenced by fire. Spinifex hummocks and the myrtaceous taxa found in the heath and mallee strata are highly flammable. After fire and subsequent rain, there is often an initial response of diverse short-lived grasses and herbaceous species. This is usually followed by a gradual decrease in diversity as species competing with spinifex in the early serial stages are outcompeted by maturing spinifex hummocks. Occasionally, dense heath, proteaceous shrubs or acacias emerge instead of spinifex (Pringle et al. 1994).

Physiognomy and composition of vegetation

SASP is characterised by abundant *Triodia* spp. (spinifex) hummock grasses. The projected foliar cover varies from scattered to close (15–50% PFC). The perennial hummock grass layer is generally dominant in terms of biomass and foliar cover. After fire, spinifex cover increases, reaches maturity and then may decline as hummocks senesce. In the survey areas north of the southern Goldfields, the most common and dominant spinifex species in SASP is *Triodia basedowii* (lobed spinifex); however, *T. scariosa* is more common in the southern Goldfields. Shrub density appears to be associated with past fire successions.

The dominant and common species by strata:

Trees:	Dominant – *Acacia aneura* Others – *Callitris* spp., *Eucalyptus gongylocarpa*
Mallees:	Dominant – *Eucalyptus concinna*, *E. ewartiana* Common – *Eucalyptus youngiana*
Tall shrubs:	Dominant – *Acacia aneura* Common – *Acacia burkittii*, *A. coolgardiensis*, *A. heteroneura* var. *jutsonii* Others – *Allocasuarina acutivalvis* subsp. *acutivalvis*, *A. spinosissima*, *Grevillea juncifolia* subsp. *temulenta*, *Hakea francisiana*
Mid shrubs:	Dominant – variable Others – *Eremophila forrestii*, *Grevillea acacioides*
Low shrubs:	Dominant – variable Common – *Microcybe multiflora* subsp. *multiflora*, *Prostanthera althoferi* subsp. *althoferi*, *Senna artemisioides* Others – *Enekbatus eremaeus*, *Homalocalyx thryptomenoides*, *Keraudrenia velutina*, *Scaevola spinescens*, *Solanum lasiophyllum*, *Thryptomene* spp., *Westringia rigida*
Perennial grasses:	Dominant – *Triodia scariosa*; occasionally *T. basedowii* Other – *Eragrostis eriopoda*
Other plant forms:	Occasional – *Dianella revoluta* (perennial herb)

Priority flora

Conospermum toddii (Priority 4) was recorded at one site.

Ecological disturbance

SASP habitats are highly flammable. Pastoralists burn spinifex grasslands to gain a few years of improved pasture from ephemeral species in the early stages of regeneration (Payne et al. 1998b; DAFWA 2006); this practice is particularly common to the north outside the southern Goldfields survey area. The consequences of this fire and grazing regime on biological diversity are not well understood, but where burning spinifex is at variance to indigenous burning practices evidence indicates it is detrimental (Prober et al. 2013). SASP communities should be permitted to mature for several years before burning again to ensure the seedbank is replenished. The long-term viability of pasture depends on allowing a recovery period.

Wind erosion is a potential concern immediately following fire when soils become exposed. However, this is not usually a problem because regrowth emerges quickly and restores stability, especially following significant rainfall events.

Gradational associations

SASP transitions into Sandplain acacia shrubland (SACS, #38) as sandy soils become shallower and loamier, and acacia tall shrubs become more prominent as spinifex becomes less conspicuous. In areas with prominent strata subordinate to the hummock grass stratum, SASP transitions into habitat types such as Sandplain mallee, spinifex woodland (SAMA, #34), Sandplain mulga, spinifex hummock grassland (SAMU, #36) or Sandplain spinifex grassland with marble gum (SAGS, #37).

In the south of the survey, SASP is replaced by Sandplain heathland (SAHE, #39) as the prominence of spinifex diminishes and myrtaceous–proteaceous species become more abundant through the understorey.

Land systems

SASP is a major habitat type in the Kirgella, Marmion and Victoria land systems.

Sandplain spinifex hummock grassland on red deep sand in the Kirgella land system

34 Sandplain mallee, spinifex woodland (SAMA)

Sampling

6 inventory sites, 64 traverse points

General information

SAMA was recognised as a subtype of Sandplain spinifex hummock grassland (SASP, #33) in the north-eastern Goldfields survey (Pringle et al. 1994). Here, it is described as a distinct habitat because of its prominence in the sandplains. SASP, which is typical of the Eremaean Botanical Province or Great Victoria Desert bioregion, is largely replaced by SAMA, which comprises mixed dry woodland components of the South-western Interzone or Coolgardie bioregion. SAMA is associated with sandplains and sand sheets throughout the north and east of the survey area.

The vegetation is very similar to Mallee, hummock grass (spinifex) woodland (MHGW, #35). The differences between these habitat types are due to edaphic factors and physiognomy, with SAMA having slightly more open canopies. SAMA occurs on sandplains and sand sheets with siliceous Red deep sand and occasional Red sandy earth soils. In comparison, MHGW occurs on calcareous eolian sandplains or calcareous plains overlain by shallow eolian sand sheets, and commonly has Calcareous loamy earth, Red–brown hardpan shallow loam or Red shallow sand or loam soils. Calcrete concretions within the MHGW soil profiles are common.

Physiognomy and composition of vegetation

SAMA typically consists of a dense understorey of *Triodia scariosa* (spinifex) under scattered to moderately close (15–30% PFC) low mallee-form eucalypt woodland dominated by *Eucalyptus concinna* (Victoria Desert mallee). The tall shrub stratum is variably developed, while mid and low shrub strata are typically poorly developed.

The dominant and common species by strata:

Trees:	Dominant – rarely present other than as emergents Other – *Acacia aneura*
Mallees:	Dominant – *Eucalyptus concinna*
Tall shrubs:	Dominant – various *Acacia* spp.; occasionally *Acacia aneura*, *A. burkittii*, *A. coolgardiensis*, *A. ramulosa* var. *linophylla*, *A. resinimarginea* Common – *Acacia hemiteles*, *A. ramulosa*, *A. tetragonophylla* Others – *Acacia nyssophylla*, *Alyxia buxifolia*, *Bursaria occidentalis*, *Grevillea sarissa* subsp. *rectitepala*, *Hakea minyma*, *Santalum spicatum*
Mid shrubs:	Dominant – variable Common – *Acacia hemiteles*, *Phebalium canaliculatum*, *Westringia cephalantha* var. *cephalantha* Other – *Prostanthera althoferi*
Low shrubs:	Dominant – rarely present as a recognisable stratum Common – *Halgania cyanea*, *Scaevola spinescens*, *Westringia rigida* Others – various *Eremophila* spp.
Perennial grasses:	Dominant – *Triodia rigidissima*, *T. scariosa*

Ecological disturbance

SAMA has very low pastoral value and is largely unaffected by grazing. As spinifex and most shrubs associated with SAMA are not favoured by livestock, pastoralists may periodically burn this habitat to gain temporary benefit from the ephemeral species that germinate in the initial regeneration after fire. The ecological consequences of this practice are not well understood, but where burning spinifex differs from indigenous burning practices it is likely to be detrimental (Prober et al. 2013). SAMA should be permitted to mature for several years before burning again to ensure the seedbank is replenished. The long-term viability of pasture depends on allowing a recovery period.

Erosion is rarely a problem because of the sandy soils and dense spinifex coverage. Only after fire, when soils are exposed, is wind erosion a potential issue. The emergence of regrowth after fire, especially after substantial rainfall events, usually restores stability.

Gradational associations

As soils become loamier and spinifex diminishes, SAMA transitions into Plain eucalypt (mallee), acacia woodland (PEAW, #43), or Sandplain acacia shrubland (SACS, #38) where acacia tall shrubs are more prominent than mallees. SAMA transitions into SASP where the hummock grass stratum becomes dominant and mallee less conspicuous.

Sandplain supporting *Eucalyptus concinna* (Victoria Desert mallee) woodland over spinifex on red deep sand in the Marmion land system

Land systems

SAMA is a major habitat type in the Kirgella and Marmion land systems and a minor habitat type in the Bannar, Cundeelee, Helag, Joseph and Victoria land systems.

35 Mallee, hummock grass (spinifex) woodland (MHGW)

Samples

8 inventory sites, 1 traverse point

General information

MHGW was first described in the WA Nullarbor survey (Waddell et al. 2010), where it is the dominant habitat type in the Zanthus land system. MHGW is primarily located in the east of the southern Goldfields survey, though there are isolated occurrences in the south.

Vegetation is similar to Sandplain mallee, spinifex woodland (SAMA, #34). The differences between these habitat types are due to edaphic factors and physiognomy, with MHGW having slightly denser canopies. MHGW occurs on sandplains and calcareous plains. The sandplains are derived from Eocene shallow marine high stands that has been overprinted with calcareous signatures derived from in situ groundwater and eolian sources. The calcareous plains are overlain by shallow eolian sand which has usually been infused with eolian and pedogenetic calcium carbonate. Typically, coarse fragments are absent from the soil surface, though occasionally sparse small calcrete concretions (2–60 mm) may be present. Below the soil surface, calcrete concretions are often present at depths typically greater than 20 cm. Soils commonly consist of Calcareous gravelly sandy (and loamy) earth and Calcareous loamy earth, with minor Calcareous gravelly shallow loam and Calcareous shallow loam on calcrete. SAMA, in comparison, is associated with sandplains of Deep red sand formed from siliceous terrigenous sediments or shallow sand sheets with similar sandy texture and red colouration.

In the central-east of the survey, MHGW is occasionally associated with low granitic pavements (Sedgeman land system) surrounded by calcareous sandplain (Zanthus land system).

Physiognomy and composition of vegetation

The projected foliar cover varies from a scattered to closed (≥15% PFC) low woodland of mallee-form eucalypts over an understorey of dense *Triodia scariosa* (spinifex). The most common dominant eucalypts are *Eucalyptus concinna* (Victoria Desert mallee) and *E. oleosa* subsp. *oleosa* (giant mallee), although others may locally dominate specific stands. Tall, mid and low shrub strata are usually poorly developed.

Fire boundary in a *Eucalyptus concinna* (Victoria Desert mallee) woodland with spinifex on a shallow sand sheet over a calcareous plain in the Zanthus land system

The dominant and common species by strata:

Mallees:	Dominant – various *Eucalyptus* spp.; often *E. concinna*, occasionally *E. cyclostoma*, *E. cylindrocarpa**, *E. gracilis*, *E. leptophylla*, *E. melanoxylon* (tree), *E. oleosa* subsp. *oleosa*, *E. transcontinentalis**
	Common – *Eucalyptus concinna*, *E. oleosa* subsp. *oleosa*
Tall shrubs:	Dominant – rarely present as a recognisable stratum
	Common – *Eremophila interstans* subsp. *interstans*, *Santalum acuminatum*
	Others – *Eremophila dempsteri**, *Exocarpos aphyllus*
Mid shrubs:	Dominant – rarely present as a recognisable stratum
	Common – *Acacia hemiteles*, *Eremophila scoparia*, *Scaevola spinescens*, *Senna artemisioides* subsp. *filifolia*
	Others – *Acacia densiflora, A. ligulata*, *Eremophila caperata*, *E. decipiens*, *Senna artemisioides* subsp. *filifolia*
Low shrubs:	Dominant – rarely present as a recognisable stratum
	Common – *Olearia muelleri*, *Scaevola spinescens*, *Westringia rigida*
	Others – *Acacia acoma*, *A. camptoclada*, *Daviesia aphylla*
Perennial grasses:	Dominant – *Triodia scariosa*

* Also known from Newbey and Hnatiuk (1984); Keighery et al. (1993)

Ecological disturbance

MHGW is largely unaffected by grazing and has very low pastoral value. Spinifex hummock grass and most shrubs associated with this habitat are not favoured by livestock. Grazing value is generally limited to seasonal opportunities after good rains which promote annual plant growth, particularly after fire.

Gradational associations

Typically, MHGW occurs as the dominant vegetation association on extensive sand sheets with clearly defined boundaries. However, at some ecotone boundaries, MHGW occurs as a component of a broader eucalypt woodland mosaic and, where sand content diminishes and loams develop on calcareous plains, often transitions into Eucalypt, false bluebush woodland (EFBW, #53), Plain eucalypt, eremophila woodland (PEEW, #59) or, less frequently, Plain eucalypt, bluebush woodland (PEBW, #52) or Sugarwood mixed chenopod shrubland (SWCS, #75).

Adjacent to the rises and pediments associated with the north-east of Fraser Range, metasedimentary rocks and calcrete platforms become prominent and the sandy terrigenous deposits become thinner or diminish; here, casuarinas become more abundant and MHGW grades into Casuarina mixed scrub shrubland (CXSS, #25).

Land systems

MHGW is the dominant habitat type in the Zanthus land system and a minor habitat type in the Charlina, Cowalinya, Noondoonia and Yandamurrina land systems, and the eastern and south-eastern occurrences of the Sedgeman land system.

Uncommon habitats in the Sandplain hummock grassland habitat group

36 Sandplain mulga, spinifex hummock grassland (SAMU)

Sampling

4 traverse points

General information

SAMU is described in the Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b). It is uncommon in the southern Goldfields. SAMU habitats typically occur as distinct patches of well-developed *Acacia aneura* (mulga) shrubland with a sparse spinifex understorey, which occur within extensive areas of spinifex grassland, such as *Sandplain spinifex hummock grassland* (SASP).

The mosaics of *A. aneura* shrubland and *Triodia* spp. grassland are largely stable systems maintained by a series of self-reinforcing fire–vegetation–soil feedbacks (Bowman et al. 2008; Murphy et al. 2010). Spinifex grasslands contain extremely flammable biomass and are fire-promoting communities, while mulga communities contain very limited fuel loads and are considered fire resistant. The 2 communities maintain a dynamic equilibrium and spatial stability over time, despite the contrasting response to fire. Spinifex requires fire to maintain vigour, and mulga – being sensitive to fire (Hodgkinson and Griffin 1982) – requires low ground biomass and fuel loads to persist.

The mechanisms governing resource capture and nutrient cycling (Tongway et al. 1989; Tongway and Ludwig 1990, 1997; Tongway 1994), which are salient features of mulga groves, are major drivers in the pedogenesis of soils associated with mulga groves. Bowman et al. (2008) considered that a soil mosaic that directly relates to the vegetation mosaics would develop with a reasonably constant climate and fire regime, in combination with mechanisms driving pedogenesis. Consequently, mulga patches within the spinifex grassland matrix become self-reinforcing in the long-term through fire–vegetation–soil feedbacks.

SAMU is often associated with transitional zones between sandplains that have Red deep sand and occasionally Red sandy earth soils and are vegetated by SASP, and sheetwash hardpan plains that have Red–brown hardpan shallow loam soils and are dominated by mulga. It also occurs adjacent to granitic protrusions within sandplains, where water accumulation and nutrient enrichment are higher due to diffuse run-on. Soils are generally Red sandy earth or Red loamy earth, with clay increasing with depth and incipient hardpan formation so that occasionally, Red–brown hardpan shallow loam soils also form in these landscape positions.

High fire frequencies throughout the spinifex-dominated matrix may restrict mulga to the more productive locations. However, Murphy et al. (2010) considered this apparent restriction of mulga more likely due to these areas facilitating their growth into reproductive maturity between fires, thereby excluding spinifex establishment. Elsewhere, high fire frequencies result in spinifex outcompeting mulga before it reaches reproductive maturity.

Physiognomy and composition of vegetation

SAMU occurs as a scattered (>10–20% PFC) mulga tall shrubland over scattered spinifex grass hummocks. *Acacia aneura* dominates the tree and tall shrub strata. Nicholas et al. (2009) showed that age and structure are related to fire history. Other acacias present include *A. coolgardiensis* (spinifex wattle), *A. ramulosa* (horse mulga) and *A. tetragonophylla* (curara). *Eucalyptus concinna* (Victoria Desert mallee) is occasionally present. The mid and low shrub strata are subordinate to the overstorey and spinifex. The understorey usually consists of young acacias, *Eremophila forrestii* (Wilcox bush) and *Solanum lasiophyllum* (flannel bush). The hummock grass stratum is dominated by *Triodia basedowii* (lobed spinifex) or *T. scariosa*, with the latter more common in the south. *Monachather paradoxus* (broad-leaved wanderrie grass) is often present.

Ecological disturbance

Comparable combinations of palatable low shrubs, commonly associated with other mulga-dominated habitat types common to sheetwash hardpan plains (such as Hardpan plain mulga shrubland, #47), occur in SAMU and, similarly, may be eliminated by excessive grazing. However, as SAMU is mainly dominated by unpalatable species, grazing seldom alters this habitat substantially, except for uncontrolled browsing by camels which can structurally affect all strata. Erosion is rarely a problem because of the diffuse nature of run-on and wind protection afforded by the predominantly ungrazed perennial vegetation.

Despite fire–vegetation–soil feedbacks maintaining relative stability between *A. aneura* and *Triodia* spp. mosaic boundaries, SAMU habitats may be at risk of fragmentation and eventual conversion into spinifex grassland because of changes in fire regimes which have resulted in more extensive and intense fires that may nullify these feedbacks (Bowman et al. 2008). Statistical modelling indicated conversion of mulga to spinifex was more probable on smaller patches of mulga shrubland subjected to increased fire activity than on larger mulga patches (Bowman et al. 2008). Small patches are more susceptible to contraction than larger patches because there is a higher proportion of transitional areas along the margins, which are also more prone to spinifex conversion.

Gradational associations

SAMU transitions into Sandplain spinifex hummock grassland (SASP, #33) as the influence of run-on diminishes and sand depth increases resulting in spinifex cover increases and *A. aneura* decreases. Where other tall shrubs increase in dominance and spinifex decreases, usually in conjunction with loamier soils, SAMU transitions into Sandplain acacia shrubland (SACS, #38).

Land systems

SAMU is a minor habitat type in the Helag, Kirgella, Marmion, Victoria and Yowie land systems.

37 Sandplain spinifex grassland with marble gum (SAGS)

Sampling

2 inventory sites

General information

SAGS is recognised as a subtype of Sandplain spinifex hummock grassland (SASP, #33) in the north-eastern Goldfields (Pringle et al. 1994) and Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b) surveys. It occurs infrequently, and is restricted to sandplains in the north-east of the southern Goldfields. SAGS is similar to SASP, differing only in the presence of scattered *Eucalyptus gongylocarpa* (marble gum) woodland over an abundant spinifex grass stratum. SAGS is associated with Red or Yellow deep sand soils within sandplains.

Physiognomy and composition of vegetation

SAGS occurs as scattered (>10–20% PFC) eucalypt trees among spinifex-dominated hummock grassland. *E. gongylocarpa* is the most common eucalypt, but *E. concinna* (Victoria Desert mallee) and *E. youngiana* (large-fruited mallee) also appear frequently in the upper stratum.

Callitris spp. are also occasionally present in the tree stratum. The tall to low shrub strata are usually poorly developed. Regular species include *Acacia heteroneura* var. *jutsonii*, *Bertya dimerostigma*, *Cryptandra recurva*, *Dianella revoluta* (blueberry lily), *Enekbatus eremaeus*, *Grevillea juncifolia* subsp. *temulenta*, *Hakea francisiana* (emu tree), *Keraudrenia velutina* and *Microcybe multiflora* subsp. *multiflora*. *Triodia basedowii* (lobed spinifex) and *T. scariosa* dominate the hummock grass stratum, with *T. scariosa* more common in the south.

Ecological disturbance

SAGS commonly occurs within sandplains and is rarely affected by grazing, except for browsing by camels. Dense spinifex cover over deep sands reduces susceptibility to wind erosion, except after fire when soils are exposed before regrowth can restore stability. However, changed fire regimes, associated with the cessation of traditional Aboriginal burning practices, are resulting in spatially widespread fires. The scale and intensity of these fires threaten the integrity of SAGS and other sandplain communities with low fire tolerance (Burrows et al. 2006). The development and implementation of managed fire regimes aligned to traditional Aboriginal burning practices could assist in protecting these communities from the devastating effects of high intensity, summer wildfires. Sand dunes often support a rich vertebrate fauna, particularly in dune swales, and thus have considerable conservation value.

Gradational associations

SAGS transitions into SASP where eucalypts disappear from the upper stratum.

Land systems

SAGS is a minor habitat type in the Kirgella, Marmion and Victoria land systems.

Sandplain spinifex grassland with *Eucalyptus gongylocarpa* (marble gum) in a swale between sand dunes in the Victoria land system

E Sandplain shrubland or woodland habitats

This group of habitat types predominantly occurs in the west of the survey area in the Youanmi South Zone, away from the spinifex hummock grasslands of the Eremaean Botanical Province (Beard 1990) and Murchison bioregion (Environment Australia 2000). The exception is Sandplain acacia shrubland (SACS, #38) which occurs in the north-east in the Eremaean Province. The other habitat types described below are more indicative of the transition from the Eremaean Province into the eastern Southwest Botanical Province and South-western Interzone and Coolgardie and Mallee bioregions. Keighery et al. (1995) also recognised a strong floristic and structural gradient from *Triodia* (spinifex) hummock grasslands (in the north) into principally ericoid shrubs, including many Myrtaceae.

In the more arid northern areas, low rainfall and grass competition reduce opportunities for shrub and tree recruitment (Nano et al. 2011), so grasslands are favoured and tend to dominate sandplains. Fire–vegetation–soil feedbacks reinforce this patterning (Bowman et al. 2008; Murphy et al. 2010). However, in the south-west, the transition from spinifex to shrub- or heath-dominated communities may be influenced by the interaction between fire frequency and higher rainfall which increases the opportunity for shrub recruitment through *Triodia* removal and increased resource availability. The increased likelihood of effective seasonal rainfall aids germination and new seedlings to persist and outcompete hummock grasses.

In the north-west, where spinifex and shrub-dominated plant associations coexist, the spinifex dominates on level red sandplains, and the shrublands become prominent on undulating yellow sandplains which often contain ferruginous gravel pisoliths in the soil profile. Traditionally, this distribution has been regarded as an edaphic association, with the soil type influencing the vegetation distribution, but recent advances in landscape evolutionary history cast fresh light on the influence of plant and microbial symbioses in the rhizosphere and the emergent properties in soil (see Soils chapter).

Most of these habitat types have very low pastoral value because of the low palatability of the vegetation and the poor water-holding capacity and low nutrient content of the sandy soils. Fire is an occasional, intense disturbance, releasing nutrients accumulated over preceding decades.

38 Sandplain acacia shrubland (SACS)

Sampling

2 inventory site, 77 traverse points

General information

SACS was described in the Murchison River catchment (Curry et al. 1994), north-eastern Goldfields (Pringle et al. 1994) and Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b) surveys where it is widely distributed. In the southern Goldfields, it most commonly occurs in association with the sandplains in the north-east. Soils are generally Red sandy earth and Red deep sand, and occasionally Red loamy earth.

The diversity and species richness are considerably less than other sandplain communities. While usually not prone to fire, after favourable seasons there may be sufficient grass through the understorey to support fire. In such circumstances, it may take decades for the tall shrub stratum to return to its pre-burn state (Curry 1986).

Physiognomy and composition of vegetation

SACS generally consists of acacia-dominated moderately close to close (>20–50% PFC) tall shrublands, occasionally mid shrublands and rarely woodlands. Trees, mallees, low shrubs and perennial grasses usually form a minor component.

The dominant and common species by strata:

Trees:	Dominant – rarely present other than as emergents; *Acacia aneura* Other – *Bursaria occidentalis*
Mallees:	Dominant – rarely present other than as emergents Others – *Eucalyptus concinna*, *E. leptopoda*, *E. youngiana*
Tall shrubs:	Dominant – *Acacia aneura*, *A. coolgardiensis*, *A. ramulosa*, *A. ramulosa* var. *linophylla* Common – *Acacia burkittii*, *A. tetragonophylla*, *Alyxia buxifolia*, *Dodonaea lobulata* Other – *Santalum spicatum*
Mid shrubs:	Dominant – variable; often *Acacia* spp. Common – *Acacia coolgardiensis*, *A. hemiteles*, *A. ramulosa*, *A. ramulosa* var. *linophylla*, *Eremophila forrestii* subsp. *forrestii*, *Phebalium canaliculatum, Senna artemisioides* subsp. *filifolia*
Low shrubs:	Dominant – *Ptilotus obovatus* Common – *Maireana georgei* (KD), *Prostanthera althoferi*, *Scaevola spinescens* (KD), *Solanum lasiophyllum* Others – *Enchylaena tomentosa* (KD), *Eremophila latrobei* (KD), *Olearia pimeleoides*, *Rhagodia eremaea*
Perennial grasses:	Dominant – *Amphipogon caricinus*, *Eragrostis eriopoda* Others – *Austrostipa elegantissima* (KD), *Monachather paradoxus* (KD), *Triodia scariosa*
Other plant forms:	Occasional – *Dianella revoluta* (perennial herb), *Leichhardtia australis* (climber)

Ecological disturbance

SACS consists mainly of unpalatable species and is not particularly attractive to livestock. Fletcher (1991) studied the impact of sheep and goat stocking rates in shrublands of similar composition to SACS and found that while the density of palatable perennial shrubs is naturally variable, the most reliable indicator species, in relation to grazing condition, are *Maireana georgei* (George's bluebush) and *Ptilotus obovatus* (cotton bush). Other palatable species include *Austrostipa elegantissima* (feather speargrass), *Enchylaena tomentosa* (ruby saltbush), *Eremophila latrobei* (warty fuchsia bush), *Monachather paradoxus* (broad-leaved wanderrie grass), *Rhagodia eremaea* (thorny saltbush) and *Scaevola spinescens* (currant bush). Fletcher also observed the density of *Eremophila forrestii* subsp. *forrestii* (Wilcox bush) decreased only during heavy stocking and the density of *Acacia aneura* (mulga) increased with grazing pressure.

Soils are not usually susceptible to accelerated erosion because the density of unpalatable, tall shrubs provides significant protection against wind erosion and rainfall impact, while dense leaf litter and sandy soils reduce surface water flows in intact habitats.

Gradational associations

SACS may abut Sandy granitic acacia shrubland (SGRS, #11) as soils become shallower and stonier, marginal to granite outcrop. SACS transitions into Sandplain spinifex hummock grasslands (SASP, #33) as soils become sandier and spinifex replaces shrubs. Conversely, with decreasing sand content, development of hardpan in the soil profile, increasing density and diversity in the understorey and decreasing PFC of the tall shrub strata, SACS may transition into Plain eucalypt (mallee), acacia woodland (PEAW, #43) in the south or Hardpan plain mulga shrubland (HPMS, #47) in the north of the survey area.

Land systems

SACS is the dominant habitat type in the Yowie land system, a major habitat type in the Kirgella and Marmion land systems and a minor habitat type in the Bandy, Bannar, Cundeelee, Cundlegum, Gransal and Helag land systems.

39 Sandplain heathland (SAHE)

Sampling

6 inventory sites, 21 traverse points

General information

SAHE is described for the first time. It occurs on gently undulating yellow sandplains with occasional gravelly sands associated with in situ weathering and pedogenesis. Soils are Yellow deep sand and Ironstone gravelly (coloured) deep sand, occasionally with Shallow sandy gravel, which contain dense ferruginous gravel pisoliths near the soil surface and throughout the subsoil.

SAHE is a sandplain habitat dominated by mid and low shrubs which form heathland rather than hummock grassland or tall acacia shrubland. It is indicative of the differentiation between sandplain vegetation dominated by heathland – more typical of the eastern Southwest Botanical Province and South-western Interzone (Beard 1990) and the Coolgardie and Mallee bioregions (Environment Australia 2000) – and the spinifex-dominated sandplains in the Eremaean Botanical Province and Murchison bioregion.

Physiognomy and composition of vegetation

SAHE consists of moderately close to closed (≥25% PFC) low shrubland, sometimes with well-developed tall or mid shrub strata. However, the structure and composition displayed immediately after fire until maturity varies because SAHE is frequently burned. Structural development is initially very scattered with low shrubs, gradually becoming more closed with stratification developing as taller shrubs outgrow the lower ericoid shrubs. While remaining irregular, because of the varied stature of maturing components, the upper strata can continue to develop structurally, eventually becoming closed and partially suppressing the lower layers to form Sandplain close mixed shrubland (SCMS, #40). Therefore, SAHE and SCMS are likely related within a sequence of vegetation succession, where time elapsed since fire influences the character of the vegetation. Within the mid and lower strata, Myrtaceae are most common, while the tall shrub stratum is variably dominated by Casuarinaceae, Fabaceae or Proteaceae. Scattered emergent mallees occasionally occur. Spinifex hummocks occur infrequently in the north, becoming less common towards the south. Other perennial grasses are not common, though sedges are regularly present.

The dominant and common species by strata:

Trees:	Dominant – rarely present other than as emergents Others – *Callitris columellaris*, *C. preissii**
Mallees:	Dominant – various emergent *Eucalyptus* spp. (*E. concinna*, *E. ebbanoensis*, *E. eremophila*, *E. horistes**, *E. leptopoda*, *E. obesa*)
Tall shrubs:	Dominant – variable; *Acacia* spp., *Allocasuarina* spp. or *Grevillea* spp. Common – *Acacia inaequiloba*, *A. neurophylla* subsp. *neurophylla*, *A. sibina*, *Allocasuarina acutivalvis**, *A. campestris**, *A. corniculata*, *Grevillea cagiana*, *G. didymobotrya* subsp. *didymobotrya*, *G. hookeriana*, *Leptospermum fastigiatum*, *L. roei* Others – *Acacia anfractuosa**, *A. consanguinea*, *A. resinimarginea*, *Banksia elderiana**, *Codonocarpus cotinifolius*, *Grevillea excelsior**, *G. juncifolia* subsp. *temulenta*, *G. pterosperma**, *Hakea cygna* subsp. *cygna*, *H. erecta**, *H. francisiana*, *H. multilineata**, *H. platysperma**, *Melaleuca hamata*
Mid shrubs:	Dominant – variable; heath shrubs; often Myrtaceae Common – *Thryptomene urceolaris* Others – *Daviesia croniniana**, *Eremaea pauciflora* var. *pauciflora*, *Goodenia pinifolia**, *Melaleuca hamata*, *Petrophile seminuda*, *P. stricta*, *Phebalium canaliculatum*, *Persoonia coriacea**, *P. helix*, *P. saundersiana**, *P. trinervis*, *Philotheca brucei**, *P. pachyphylla*, *Thryptomene kochii**
Low shrubs:	Dominant – variable; heath shrubs; often Myrtaceae Common – *Homalocalyx thryptomenoides*, *Melaleuca cordata* Others – *Balaustion pulcherrimum**, *Beaufortia micrantha*, *Boronia ternata**, *Calytrix* spp., *Chamelaucium pauciflorum**, *Cyanostegia microphylla**, *Dampiera lavandulacea*, *D. luteiflora*, *D. stenostachya**, *Erichsenia uncinata**, *Euryomyrtus leptospermoides**, *E. patrickiae*, *Halgania cyanea*, *Hibbertia rostellata*, *Hysterobaeckea ochropetala**, *Jacksonia nematoclada*, *Phebalium filifolium**, *Pityrodia lepidota*, *Platysace effusa*, *Prostanthera grylloana*, *Stenanthemum stipulosum*, *Tetratheca efoliata**, *Verticordia chrysantha*, *V. picta**, *V. pritzelii**, *V. roei* subsp. *roei**
Perennial grasses:	Dominant – rarely present as a recognisable stratum Others – *Triodia irritans*, *T. rigidissima**, *T. scariosa*
Other plant forms:	Occasional – *Lepidobolus preissianus* (sedge), *Lepidosperma drummondii* (sedge), *L. pruinosum* (sedge)

* Also known from Beard (1976); Newbey and Hnatiuk (1988); Newbey et al. (1995)

Priority flora

Chamelaucium sp. *Koolyanobbing* (V. Clarke 644, Priority 1) was recorded at two sites.

Ecological disturbance

SAHE consists almost entirely of species not usually grazed by livestock and is not particularly threatened by grazing. However, it is prone to fire (Beard 1976). Regeneration from fire is primarily by seed and coppicing. The variable physiognomy and floristic composition are likely to reflect temporal stages in the regeneration and ensuing succession after fire. The succession sequence outlined in the Physiognomy section is one where early, seral species appearing immediately after fire are gradually replaced through senescence or give way in competition to late seral, taller species. Species richness decreases with increased time after disturbance (fire) and variations over time are controlled by plant life histories, differential growth rates, structure, and survivorship (Egler 1954; Picket et al. 1987; Collins et al. 1995). For example, short-lived pioneer species, such as *Codonocarpus cotinifolius* (native poplar) and *Grevillea excelsior* (flame grevillea), are stimulated by fire and die after a period of years, disappearing and only persisting in the soil seedbank, or in more recently burned adjoining patches, until the next fire. These short-lived pioneer species are replaced by slower growing and late successional species, such as *Acacia* spp. and *Allocasuarina* spp.

Studies in vegetation communities containing equivalent species and soil types suggest that SAHE, when remaining unburned, shows signs of structural senescence about 45 years after fire (Gosper et al. 2012). They also concluded that communities with a diverse heath layer (with or without emergent mallees) are fire-maintained communities: they rely on periodic burning to maintain diversity and vigour (see photo sequence in SCMS, #40).

Gradational associations

SAHE transitions into Sandplain close mixed shrubland (SCMS) where tall scrub increases in density to form extensive thickets. SAHE transitions into Lateritic allocasuarina scrub (LASC, #18) where sands become gravellier and thickets are dominated by *Allocasuarina* spp. In the south, SAHE transitions into Sand sheet mallee heath (SAMH, #41) as mallee begins to dominate the upper strata, indicating the transition of the Coolgardie bioregion into the Mallee bioregion.

Land systems

SAHE is a major habitat type in the Joseph land system and minor habitat type in the Bannar, Hann and Hyden land systems.

Spring wildflowers in a sandplain heathland in the Bannar land system

40 Sandplain close mixed shrubland (SCMS)

Sampling

11 inventory sites, 29 traverse points

General information

SCMS was first described in the Sandstone, Yalgoo and Paynes Find area survey (Payne et al. 1998b). It typically occurs on gently undulating yellow sandplains in the west of the southern Goldfields. It also infrequently occurs on sandplain remnants isolated from the larger, contiguous sections of sandplain. Soils are indicative of a diverse suite of vegetation in a significant transition zone. They are most commonly Yellow deep sand, with minor Acid gravelly sandy earth, Deep sandy gravel, Loamy gravel, Yellow sandy earth and Red deep sand soils.

SCMS indicates change from the red sandplains dominated by spinifex hummock grassland in the Eremaean Botanical Province (Beard 1990) and Murchison bioregion (Environment Australia 2000) to the yellow and gravelly sandplain vegetated by proteaceous and myrtaceous heath-scrubland typical of the eastern Southwest Botanical Province and South-western Interzone, and the Coolgardie and Mallee bioregions.

Physiognomy and composition of vegetation

SCMS consists of close to closed (>30% PFC) shrubland or thickets when mature, though where the structure is still developing it is moderately close (>20–30% PFC). Tall scrub usually occurs as a single-layered community, with the dominant species being those of this canopy layer. Sometimes the mid shrub stratum is dominant; however, this is likely to represent a semi-mature cohort in the recovery phase after fire. Therefore, vegetation height is likely to depend on time elapsed since the last fire. Low shrubs are often scattered, though at the margins an understorey of heath species may gradually increase in dominance to form intermediate structures between the tall and low stratum. Trees and perennial grasses are typically poorly represented. Infrequent stands of emergent mallees, such as *Eucalyptus leptopoda* (Tammin mallee) and *E. rigidula* (stiff-leaved mallee), are occasionally present.

The dominant and common species by strata:

Trees:	Dominant – rarely present other than as emergents Common – *Callitris columellaris*, *C. preissii*
Mallees:	Dominant – various emergent *Eucalyptus* spp. Common – *Eucalyptus leptopoda*, *E. leptopoda* subsp. *leptopoda*, *E. rigidula* Others – *Eucalyptus concinna*, *E. horistes**, *E. loxophleba* subsp. *lissophloia*
Tall shrubs:	Dominant – variable; *Acacia* spp., *Allocasuarina* spp., *Melaleuca* spp. Common – *Acacia resinimarginea*, *A. sibina*, *Allocasuarina corniculata*, *Melaleuca hamata* Others – *Acacia consanguinea*, *A. coolgardiensis*, *Allocasuarina acutivalvis**, *A. campestris**, *A. spinosissima*, *Alyxia buxifolia*, *Grevillea pterosperma**, *Hakea francisiana*, *H. multilineata**, *Leptospermum fastigiatum*, *Santalum acuminatum*
Mid shrubs:	Dominant – variable; heath shrubs; often Myrtaceae Common – *Beyeria sulcata* var. *sulcata*, *Melaleuca hamata*, *Phebalium canaliculatum*, *Thryptomene urceolaris*

Low shrubs:	Dominant – variable; heath shrubs Common – *Beyeria sulcata* var. *sulcata*, *Melaleuca cordata* Others – *Leucopogon hamulosus*, *Melaleuca calyptroides*, *Pityrodia lepidota*, *Prostanthera grylloana*, *Scaevola spinescens*
Perennial grasses:	Dominant – rarely present as a recognisable stratum Others – *Triodia desertorum*, *T. scariosa*, *T. tomentosa*
Other plant forms:	Occasional – *Dianella revoluta* (perennial herb)

* Also known from Beard (1976); Newbey et al. (1995)

Priority flora

Allocasuarina eriochlamys subsp. *grossa* (Priority 3) and *Calytrix creswellii* (Priority 3) were recorded at one site each.

Ecological disturbance

SCMS is not particularly threatened by grazing because it consists almost entirely of species not usually grazed. Along the western survey border, much appears to have been cleared for agriculture. The dense vegetation provides effective protection against erosion. However, the closed nature of these shrublands and dense, continuous low fuels influence the susceptibility to fire. Intense and extensive fires destroy the shrubland's protective canopy, leaving soils exposed and vulnerable to wind erosion. Since regeneration is largely by seed, the soil surface can remain bare for extended periods until effective rains facilitate germination and enable new seedlings to persist and develop cover. Where present, low heath species may recruit first in the initial recovery after fire, later suppressed as the taller components of these shrublands resume canopy dominance. Therefore, in some locations, SCMS may represent a structurally mature expression along a sequence of vegetation succession between Sandplain heathland (SAHE, #39) and SCMS, influenced by time elapsed since fire.

With increasing time after fire, SCMS becomes progressively more flammable as spatial continuity develops and fuel mass accumulates (Beard 1976; O'Donnell et al. 2011a). Modelling of these closed shrub assemblages suggests intervals between fires are typically short – with the timescale of a fire regime equal to 46 years – when compared to woodland habitat types common to the Great Western Woodlands (such as SAMH, #41; CEWS, #51; PESW, #58). Fire intervals are also strongly influenced by fuel structure and age (O'Donnell et al. 2011a).

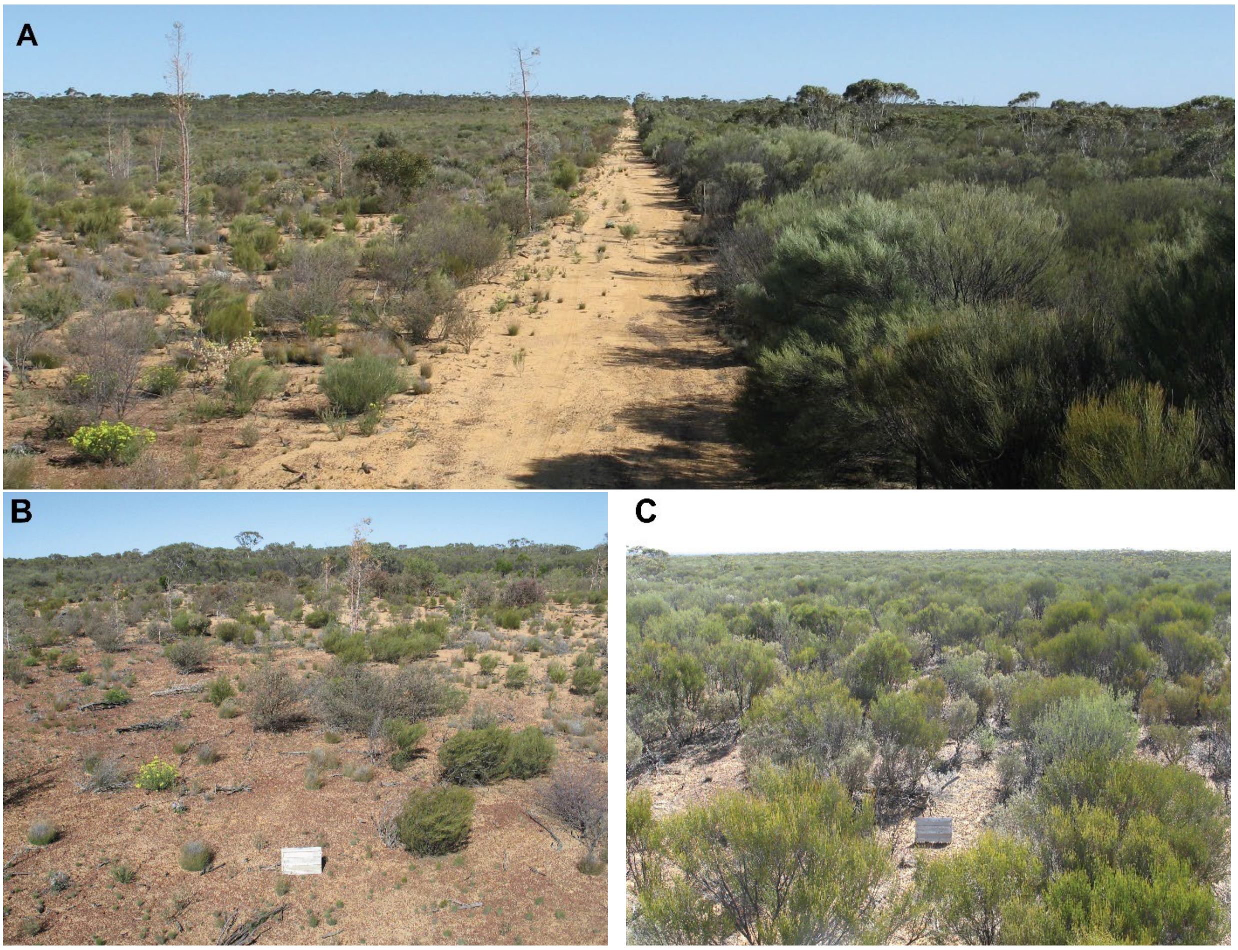
Gradational associations

SCMS merges into SAHE where tall scrub–thickets become less dense and the lower shrub stratum, populated by mainly Myrtaceae and Proteaceae, becomes the dominant cover. Where SCMS merges with SAHE, there are often intermediate stages as ericoid shrubs increase in prominence through the low shrub stratum. At sandplain margins, SCMS often transitions into Lateritic allocasuarina scrub (LASC, #18) where the soil becomes shallower gravelly sand, and *Allocasuarina* species increase in prominence through the upper strata.

In the north of the survey, SCMS is similar to Sandplain acacia shrubland (SACS, #38), but often has denser vegetation with more floristic components typically associated with the Southwest Botanical Province than the Eremaean Botanical Province. In the south, as the Coolgardie bioregion transitions into Mallee bioregion, SCMS transitions into Sand sheet mallee heath (SAMH, #41) as mallee begin to dominate the upper strata.

Land systems

SCMS is a major habitat type in the Hyden and Joseph land systems and a minor habitat type in the Bandy, Bannar, Sedgeman and Wallaroo land systems.



An example of vegetation succession and how time after fire influences the character of sandplain communities: A) a sandplain community divided by a track on a gravel sand sheet in the Joseph land system; B) the vegetation (left-hand side of the track) in the initial phase of recovery after recent fire and resembles a Sandplain heathland; C) more structurally mature vegetation (right-hand side of the track) typical of a Sandplain close mixed shrubland

41 Sand sheet mallee heath (SAMH)

Sampling

8 inventory sites

General information

SAMH is described for the first time. It occurs on gently undulating sandplains whose soils are predominantly sandy-surfaced duplexes. Yellow–brown shallow sandy duplex soil predominates and is sometimes alkaline; occasionally SAMH occurs on Grey (shallow or deep) sandy duplexes, Yellow–brown shallow loam duplex, sometimes alkaline, and Pale deep sand soils.

SAMH indicates the southern transition from heathland, which is typical of the southern sandplain habitats in the Coolgardie bioregion (Environment Australia 2000), to the mallee eucalypt-dominated low woodlands over heath of the Mallee bioregion or Roe Botanical District in the Mallee Region (Beard 1990).

Physiognomy and composition of vegetation

SAMH consists of close to closed (≥30% PFC) low eucalypt (mallee) woodland over varied shrub strata, dominated by Myrtaceae and Proteaceae. There is considerable variability in physiognomy and composition, with time elapsed since fire strongly influencing the height and density of the mallee component, which may secondarily affect the structure of the understorey. Dense, closed stands of mallee with a sparse low shrub understorey, typically consisting of *Melaleuca* species, indicate areas which have not been burned for extended periods. Elsewhere, in areas recovering from fire, a more structurally variable understorey ranges between heath and scrub. Therefore, the physiognomy and composition within a SAMH community is likely to be a temporal sequence of vegetation succession, where time elapsed since fire influences the character. Where ecotone boundaries occur within the sandplains and SAMH merges with Sandplain heathland (SAHE, #39), the understorey will consist of more ericoid species within the transition gradient. Perennial grasses are not common.

The dominant and common species by strata:

Mallees:	Dominant – various *Eucalyptus* spp. (*E. alipes*, *E. cylindriflora*, *E. eremophila*, *E. eremophila* subsp. *eremophila*, *E. obesa*, *E. platycorys*, *E. rigidula*) Common – *Eucalyptus eremophila*, *E. platycorys* (when other species are dominant) Other – *Eucalyptus incrassata**
Tall shrubs:	Dominant – variable; *Allocasuarina* spp., *Grevillea* spp., *Melaleuca* spp. Common – *Grevillea didymobotrya* subsp. *didymobotrya*, *G. oncogyne*, *Melaleuca eleuterostachya*, *M. halmaturorum*, *M. hamata*, *M. lateriflora*, *M. uncinata**, *Petrophile stricta* Others – *Allocasuarina acutivalvis* subsp. *acutivalvis*, *Santalum acuminatum*
Mid shrubs:	Dominant – variable; heath shrubs; often Myrtaceae or Proteaceae Common – *Grevillea huegelii*, *Hakea newbeyana*, *Melaleuca hamata*, *M. lateriflora*, *M. undulata**, *Petrophile stricta*, *Thryptomene kochii**
Low shrubs:	Dominant – variable; heath shrubs; often Myrtaceae Common – *Cyathostemon ambiguus*, *Daviesia aphylla*, *Dodonaea bursariifolia**, *Leucopogon* spp., *Melaleuca cordata**, *M. johnsonii*, *M. thyoides*, *Olearia ramosissima**, *Phebalium filifolium**
Other plant forms:	Occasional – *Cassytha* spp. (climber), *Lepidosperma* spp. (sedge)

* Also known from Beard (1976); Hopkins and Robinson (1981); Newbey and Hnatiuk (1988); Newbey et al. (1995)

Priority flora

Melaleuca similis (Priority 1) and *Verticordia sieberi* var. *pachyphylla* (Priority 1) were recorded at one site.

Ecological disturbance

SAMH consists almost entirely of species not usually grazed by livestock and is not particularly threatened by grazing. However, it is prone to fire. Most fires in mallee communities result in the death of stems and branches because of the low canopy height, although this is typically followed by synchronous resprouting from lignotubers to form new stems (Clarke et al. 2010). The effects of a single fire event can become imprinted on the vegetation (Hopkins and Robinson 1981; Clarke et al. 2010) because former single-stemmed eucalypts develop the multi-stemmed mallee form. Subsequent fires can result in repeating episodes of resprouting, which reinforces the multi-stemmed form. Hopkins and Robinson (1981) described this mallee heath formation as a 'pyric disclimax': where mallee heath is considered a fire-induced structural change from a 'Low Woodland A formation' (Muir 1977) or 'Woodland' (NVIS 2017). Hopkins and Robinson (1981) demonstrated that floristic structural change was induced by fire, when they studied vegetation and soil across a known fire boundary, and proved there was edaphic and floristic continuity. This precluded the possibility of structural disconnection due to an ecotone corresponding with the fire boundaries.

An example of how time since fire influences the physiognomy and composition of a sandplain mallee heath community: A) a sandplain mallee heath community divided by a track in the Forrestiana land system; B) the vegetation (left-hand side of the track) in the recovery phase after fire; C) the more structurally developed vegetation community (right-hand side of the track)

Litter accumulation tends to be concentrated around the bases of individual trees with the interpatches between trees remaining relatively sparse, aside from scattered heath shrubs. After fire, very slow rates of regeneration (Hopkins and Robinson 1981) and sparsity of interpatch vegetation necessitate a significant period for these communities to regain structural density, accumulate litter and increase spatial continuity before they are again sufficiently flammable to carry a fire. The propensity of mallee communities to burn is moderately dependent on fuel age and, therefore, increases with time since fire, with modelling suggesting fire-return intervals of less than 66 years (O'Donnell et al. 2011a). Studies on the response of mallee communities to time since last fire revealed these communities are modified, but not maintained, by fire and are less susceptible to fire interval effects (Gosper et al. 2012). The resilience of mallee communities to long intervals without fire was demonstrated in the ongoing development in stature in long unburnt stands, dominated by resprouter vegetation, which showed no signs of requiring fire to maintain vigour or stimulate diversity (Gosper et al. 2012).

Gradational associations

Where mallee is less conspicuous in the upper strata, SAMH transitions into Sandplain heathland (SAHE, #39), indicating the transition from the Mallee bioregion into the Coolgardie bioregion in association with changing edaphic and climatic conditions. SAMH transitions into Sandplain close mixed shrubland (SCMS, #40) where tall scrub–thickets increase in density and rival the dominance of mallees. Close to lunettes, SAMH transitions into Lakeside (sand sheet) eucalypt woodland with shrubs (LSES, #64) as sand content and alkalinity increase.

Land systems

SAMH is a major habitat type in the Hann, Forrestiana and Newdegate land systems.

42 Sandplain crest eucalypt stand (SCES)

Sampling

7 inventory sites, 4 traverse points

General information

SCES is described for the first time. Occurring on crests and rises within sandplains, SCES is a small component within the extensive plains that dominate the gently undulating yellow sandplains of the South-western Interzone (Beard 1990) and the Coolgardie and Mallee bioregions (Environment Australia 2000). Soils range from Yellow–brown deep sandy duplex (sometimes alkaline) to Yellow deep sand occasionally with ferruginous gravel pisoliths in the soil profile, and Calcareous loamy earth sometimes with calcareous concretions in the soil profile.

Physiognomy and composition of vegetation

SCES consists of scattered to close (15–50% PFC) stands of eucalypts, often in mallee form, with variably developed tall to low shrub strata. The mallee form of some eucalypts, which usually occur as single-stemmed trees, is due to coppicing after fire. Similarly, the variability in foliar cover is likely to be influenced by the time between fires and seasonal conditions during the recovery period after fire, as well as the frequency and intensity of past fires. Perennial grasses are rarely present in the south, though *Triodia* spp. (spinifex) become increasingly common in the northern limits of this habitat.

The dominant and common species by strata:

Trees:	Dominant – rarely present as a recognisable stratum Other – *Callitris* spp.
Mallees:	Dominant – various *Eucalyptus* spp.; occasionally *E. ebbanoensis* subsp. *ebbanoensis*, *E. platycorys*, *E. transcontinentalis*, *E. urna* Common – *Eucalyptus leptopoda*, *E. platycorys*, *E. transcontinentalis*
Tall shrubs:	Dominant – variable; *Acacia* spp., *Allocasuarina* spp., *Melaleuca* spp.

	Common – *Acacia hemiteles*, *A. nyssophylla*, *A. resinimarginea*, *Allocasuarina acutivalvis* subsp. *acutivalvis*, *A. corniculata*, *Melaleuca hamata*, *Santalum spicatum* Others – *Acacia consanguinea*, *Allocasuarina acutivalvis* subsp. *prinsepiana*, *Alyxia buxifolia*, *Leptospermum roei*, *Melaleuca eleuterostachya*
Mid shrubs:	Dominant – variable Common – *Beyeria sulcata* var. *sulcata*, *Eremophila caperata*, *Melaleuca hamata*, *Persoonia coriacea**, *Phebalium canaliculatum*
Low shrubs:	Dominant – variable Common – *Scaevola spinescens*, *Westringia cephalantha*, *W. cephalantha* var. *cephalantha* Others – *Coopernookia strophiolata*, *Philotheca brucei*, *Stenanthemum stipulosum*
Perennial grasses:	Dominant – rarely present as a recognisable stratum, though *Triodia* spp. feature more prominently in the north Others – *Triodia irritans*, *T. scariosa*

* Also known from Beard (1976)

Ecological disturbance

SCES is not particularly threatened by grazing because it consists almost entirely of species not usually attractive to livestock. Erosion is rarely a problem on the sandy-surfaced soils, particularly where unburnt mallee stands are close and provide some protection from strong winds. Wind erosion is only a potential issue when soils are exposed after fire. Stability is restored with the rapid emergence of regrowth after fire.

Being on crests and surrounded by fire-prone habitat types such as Sandplain heathland (SAHE, #39) and Sandplain close mixed shrubland (SCMS, #40), SCES could also be considered fire-prone. While SCES occasionally experiences wildfires, there are also examples where it has remained unburned among its surroundings. The eucalypt stands can form partial fire barriers, particularly to low intensity fires. The development of duplex soils, likely driven by the biological interaction between the eucalypts and soil microbes (Verboom and Pate 2013; Reith et al. 2019) may have a role in limiting understorey development (Nulsen et al. 1986), thereby affecting fuel loads. This can subsequently reduce the effect of fire on the eucalypt stands and the vegetation communities in the lee of these stands.

Dune crest supporting a stand of *Eucalyptus platycorys* (Boorabbin mallee) and *E. transcontinentalis* (redwood) overlooking Sandplain close mixed shrubland in a broad swale between another dune crest and a stand of eucalypts in the Joseph land system

Gradational associations

Since SCES occurs on sand dune crests, it typically transitions downslope into the sandplain habitat types common to the plains or swales below, such as SAHE and SCMS.

Land systems

SCES is a minor habitat type in the Joseph land system.

F Plains transitional to sandplain habitats

This group typically occurs as shrubland or woodland habitat types on sheetwash plains situated between alluvial lowlands and interfluves of either sandplains or rocky uplands. Plain eucalypt (mallee), acacia woodland (PEAW, #43) and Plain York gum, acacia woodland (PYAW, #44) occur on sheetwash plains on Red–brown hardpan shallow loam or Red loamy earth soils. While they occur on similar topographic positions and soils, they are geographically distinct. PYAW is related to the Yalgoo bioregion and is common in the north-west of the survey associated with the Bimbijy Sandplains Zone. PEAW is related to the Murchison bioregion and is more common to land systems in the north-east of the survey. Both of these habitat types represent the transition between the acacia-dominated tall shrublands of the Eremaean Botanical Province and the eucalypt-dominated woodlands in the South-western Interzone and Coolgardie bioregion.

Plain native pine, heathland (PINH, #45) and Plain native pine, acacia woodland (PINW, #46) are similar in having an upper stratum dominated by *Callitris* (native pine) but differ in their understoreys. PINH has a myrtaceous–proteaceous heathland understorey and PINW has an understorey of acacias. These 2 habitat types are typically associated with landforms where the soils – gravelly sands or sandy duplexes – differ from the adjacent or surrounding yellow sandplains of the Youanmi South Zone.

43 Plain eucalypt (mallee), acacia woodland (PEAW)

Sampling

13 inventory sites, 182 traverse points

General information

PEAW is described for the first time. This habitat is a low woodland co-dominated by mulga and mallee. It is common in the north-east of the survey and typically occurs on extensive sheetwash plains between erosional uplands and depositional lowland habitat types adjacent to lake country. The dominant soils are Red shallow loam with a calcrete hardpan, Red–brown hardpan and Red loamy earth. Calcareous loamy earth, sometimes with a calcrete hardpan at depth, is a minor soil.

PEAW has a similar species assemblage to Calcareous plain eucalypt (mallee), acacia shrubland (CEAS) which is described by Pringle et al. (1994) in the north-eastern Goldfields survey. However, the 2 habitat types are considered different because PEAW usually has Red–brown (and occasional calcrete) hardpans but neutral loamy soil, and CEAS occurs on deep Calcareous red earth, often over calcrete.

Physiognomy and composition of vegetation

PEAW occurs as a scattered to moderately close (>10–30% PFC) low woodland typically co-dominated by *Acacia aneura* (mulga) and mallees, most often *Eucalyptus concinna* (Victoria Desert mallee). The mid and low shrub strata are well developed. Perennial grasses are variably distributed.

The dominant and common species by strata:

Trees:	Dominant – *Acacia aneura* Common – *Casuarina pauper* Other – *Brachychiton gregorii*
Mallees:	Dominant – mainly *Eucalyptus concinna*; occasionally *E. griffithsii* (near greenstones), *E. leptopoda* (near sandplains), *E. oleosa**, *E. rigidula*
Tall shrubs:	Dominant – *Acacia aneura*, *A. burkittii*; occasionally *A. ramulosa* (in sandplains) Common – *Acacia ramulosa* var. *ramulosa*, *A. tetragonophylla*, *Alyxia buxifolia*, *Eremophila alternifolia*, *Exocarpos aphyllus*, *Santalum spicatum* Other – *Eremophila oppositifolia*
Mid shrubs:	Dominant – *Acacia hemiteles* (KI), *Dodonaea lobulata* (KI), *Senna artemisioides* subsp. *filifolia* (KI) Common – *Eremophila granitica*, *E. latrobei* (KD), *Scaevola spinescens* (KD), *Sida calyxhymenia* (KD) Others – *Eremophila decipiens*, *E. glabra*, *E. scoparia*
Low shrubs:	Dominant – *Olearia muelleri*, *Ptilotus obovatus*, *Scaevola spinescens* (KD) Common – *Maireana sedifolia*, *M. triptera* Others – *Enchylaena tomentosa* (KD), *Rhagodia drummondii* (KD), *Solanum lasiophyllum*
Perennial grasses:	Dominant – rarely present as a recognisable stratum Common – *Austrostipa elegantissima* (KD) Others – *Austrostipa scabra*, *Eriachne helmsii*, *Triodia scariosa*
Other plant forms:	Common – *Leichhardtia australis* (climber)

* Also known from Keighery et al. (1992)

Ecological disturbance

The variety and density of palatable mid and low shrubs is the most reliable indication of grazing pressure, which typically occurs under mallees and tall shrubs. In grazed areas, reductions in palatable species tend to occur first in the open interpatch areas, and subsequently in the relatively protected, more fertile patches under the mallees and shrubs. Palatable shrubs include *Enchylaena tomentosa* (ruby saltbush), *Ptilotus obovatus* (cotton bush), *Rhagodia drummondii* (lake-fringe rhagodia) and *Scaevola spinescens* (currant bush). The perennial *Austrostipa elegantissima* (feather speargrass) is also very sensitive to grazing pressure and indicates good resource condition when abundant.

Erosion is generally not an issue on PEAW when there is an abundance of low shrubs and leaf litter under fertile patches. However, where vehicle tracks cause local incision, overland flow (sheetwash) is disrupted, and water flow concentrates down tracks, causing gully erosion along the track and water starvation of habitats downslope.

A track in a Plain eucalypt (mallee), acacia woodland where the grader has cut below the level of the plain and sheet flow has channelled down the track causing erosion

Gradational associations

In uplands adjacent to footslopes and low rises, PEAW commonly abuts Stony casuarina, dodonaea shrubland (SCDS, #15) in greenstone-dominated landscapes and Granitic pediment eucalypt, tall shrub thicket (GETT, #12) around granitic outcrop. As soils become sandier, PEAW transitions into Sandplain acacia shrubland (SACS, #38) or, where spinifex dominates the vegetation on sandy soils, Sandplain mallee, spinifex woodland (SAMA, #34).

As gently inclined sheetwash plains become level and mallees are replaced by trees, – such as *Eucalyptus salmonophloia* (salmon gum) and *E. transcontinentalis* (redwood) – PEAW often transitions into Plain eucalypt, eremophila woodland (PEEW, #59) on broad plains and Plain eucalypt, saltbush woodland (PESW, #58) in the alluvial tracts with heavier duplex and clay soils.

Closer to salt lake systems, the soil becomes heavier textured and calcareous as a result of increased concentration of calcium carbonate derived from shallower groundwater and dust blown from lake surfaces. In these situations, PEAW transitions to Calcareous casuarina, acacia shrubland or woodland (CCAS, #80) as *Casuarina pauper* (black oak) replaces mallees to become the dominant overstorey, and the soils often develop a calcrete hardpan. Where the entire profile becomes highly calcareous and slightly saline, *Maireana sedifolia* (pearl bluebush) becomes more conspicuous in the understorey and the Calcareous pearl bluebush shrubland (CPBS, #31) habitat type develops.

In the north where mulga dominates the overstorey, siliceous (red–brown) hardpans develop in the subsoil and PEAW transitions into Hardpan plain mulga shrubland (HPMS, #47).

Land systems

PEAW is the dominant habitat type in the Helag land system, a major habitat type in the Kirgella and Yowie land systems and a minor habitat type in the Cundeelee, Deadman, Doney, Illaara, Lakeside, Marmion and Moriarty land systems.

Eucalyptus griffithsii (Griffith's grey gum) woodland with *Acacia burkittii* (sandhill wattle) in the Helag land system

44 Plain York gum, acacia woodland (PYAW)

Sampling

5 inventory sites

General information

PYAW was first described in the Sandstone, Yalgoo and Paynes Find area survey (Payne et al. 1998b). It is a low woodland co-dominated by acacias and mallees. PYAW occurs between uplands on sheetwash plains typically associated with soils derived from granite, and lowland habitat types adjacent to lake country. Soils are typically Red–brown hardpan shallow loam, and occasionally shallow non-cracking clay soils with hardpan at depth or Red loamy earth without a hardpan within 80 cm.

When first described, the dominant eucalypt was identified as *E. loxophleba*, a species recognised by Beard (1990) as a regional dominant along the middle of the northern boundary of the Southwest Botanical Province, hence the reference to York gum in this habitat type's name. However, reclassification has identified a subspecies of *E. loxophleba*, and the eucalypt formerly identified as dominant in PYAW habitats is now identified as *E. loxophleba* subsp. *lissophloia*, with the common name 'smooth-barked York gum'. For continuity with other DPIRD rangeland surveys, publications and database applications, the name PYAW has been retained, despite *E. loxophleba* subsp. *lissophloia* not being the species with the common name York gum.

Occupying a similar landscape position and co-dominated by acacias and mallees, PYAW is similar to Plain eucalypt (mallee), acacia woodland (PEAW, #43). The major difference is the dominance of *E. loxophleba* subsp. *lissophloia* rather than *E. concinna* (Victoria Desert mallee). PYAW is also geographically distinct from PEAW, being more common in the north-west of the survey and associated with the Bimbijy Sandplains Zone.

Physiognomy and composition of vegetation

PYAW occurs as a scattered to close (15–50% PFC) low woodland, or tall shrubland where eucalypts are sparser than acacias. *E. loxophleba* subsp. *lissophloia* is the dominant mallee. The tall shrub stratum is invariably dominated by acacias. The mid shrub stratum is variably developed, while the low shrub stratum is typically well developed. Perennial grasses are patchily distributed.

A common feature of PYAW is tree-based clumps – where particular suites of species grow under eucalypt canopies among leaf litter – characterised by mid and low shrubs rather than the acacias and other taller shrubs that predominate between eucalypts.

Eucalyptus loxophleba subsp. *lissophloia* mallees over a tall shrubland dominated by *Acacia ramulosa* var. *ramulosa* on a red loamy earth soil in the Pindar land system

The dominant and common species by strata:

Trees:	Dominant – rarely present as a recognisable stratum Others – *Acacia aneura*, *Brachychiton gregorii*
Mallees:	Dominant – *Eucalyptus* spp., often *E. loxophleba* subsp. *lissophloia* Common – *Eucalyptus kochii* subsp. *plenissima*, *E. loxophleba* subsp. *lissophloia* Others – *Eucalyptus celastroides* subsp. *celastroides*, *E. griffithsii*
Tall shrubs:	Dominant – various *Acacia* spp. often *Acacia burkittii*, occasionally *A. acuminata*, *A. ramulosa* var. *linophylla*, *A. ramulosa* var. *ramulosa* Common – *Acacia nyssophylla*, *A. tetragonophylla* Others – *Acacia aneura*, *Alyxia buxifolia*, *Dodonaea viscosa* subsp. *angustissima*, *Eremophila oppositifolia*, *Santalum spicatum*
Mid shrubs:	Dominant – variable Common – *Scaevola spinescens* (KD), *Senna artemisioides* subsp. *filifolia* (KI), *Philotheca brucei* Others – *Eremophila decipiens*, *E. georgei*, *E. granitica*
Low shrubs:	Dominant – variable; often *Ptilotus obovatus* Common – *Maireana georgei* (KD), *Olearia muelleri*, *Scaevola spinescens* (KD) Others – *Enchylaena tomentosa* (KD), *Maireana thesioides* (KD), *M. triptera*, *Rhagodia drummondii* (KD)
Perennial grasses:	Dominant – rarely present as a recognisable stratum Common – *Austrostipa elegantissima* Other – *Austrostipa scabra*

Ecological disturbance

PYAW has some resilience to overgrazing because a significant proportion of foliage is unreachable and unpalatable. Grazing is typically concentrated in the suite of palatable species associated with tree-based clumps under the mallees and shrubs, though reductions in palatable species tend to occur first in the open interpatch areas. Grazing can reduce the mix and abundance of palatable perennial low shrubs, such as *Enchylaena tomentosa* (ruby saltbush), *Maireana georgei* (George's bluebush), *M. thesioides* (lax bluebush), *Ptilotus obovatus* (cotton bush), *Rhagodia drummondii* (lake-fringe rhagodia) and *Scaevola spinescens* (currant bush). The decline of palatable species may result in some increase in unpalatable acacias, eremophilas and sennas. Erosion does not appear to be a major problem. However, where vehicle tracks disrupt overland flow (sheetwash) and concentrate water flow down tracks, gully erosion and water starvation downslope of the tracks may occur.

Gradational associations

In uplands adjacent to breakaway footslopes, PYAW distinctly abuts Breakaway footslope eucalypt woodland with chenopod understorey (BECW, #26). Where soils are deeper and coarser, and the acacia component increases in dominance, PYAW may transition into Sandplain acacia shrubland (SACS, #38), Sandplain close mixed shrubland (SCMS, #40), or Plain native pine, acacia woodland (PINW, #46) where *Callitris* spp. increases in prominence. Conversely, PYAW commonly transitions downslope into Plain eucalypt, saltbush woodland (PESW, #58) as chenopods become more conspicuous and eucalypt trees replace mallees, and soils become heavier textured.

Land systems

PYAW is the dominant habitat type in the Pindar land system and a major habitat type in the Euchre land system.

45 Plain native pine, heathland (PINH)

Sampling

4 inventory sites, 1 traverse point

General information

PINH is described for the first time. It is characterised by *Callitris* spp. (native pines), which dominate the tall shrub stratum, over a myrtaceous–proteaceous heathland understorey. PINH is associated with gently undulating sandplains in the south-west of the survey. It typically occurs on low rises and crests on Ironstone gravelly soils within sandplains, with minor Deep yellow sand soils.

Physiognomy and composition of vegetation

PINH occurs as a scattered (>10–20% PFC) woodland or tall shrubland of *Callitris* spp. among a moderately close to closed (>20% PFC) myrtaceous–proteaceous heathland. The mid and low shrub strata are well developed. Perennial grasses are rare, though in the northern limits of this habitat type, *Triodia scariosa* (spinifex) may be present. Sedges are common.

The dominant and common species by strata:

Mallees:	Dominant – rarely present other than as emergents Common – *Eucalyptus leptopoda*
Tall shrubs:	Dominant – *Callitris columellaris*, *C. preissii* Common – *Allocasuarina acutivalvis* subsp. *acutivalvis*, *Banksia erythrocephala* var. *erythrocephala*, *B. pallida*, *Hakea cygna* subsp. *cygna*, *Hakea erecta**, *H. newbeyana* Others – *Allocasuarina campestris*, *A. corniculata**, *Hakea meisneriana*, *Leptospermum roei**, *Persoonia coriacea*, *P. saundersiana**, *P. trinervis*
Mid shrubs:	Dominant – *Melaleuca cordata*; occasionally *Grevillea didymobotrya* subsp. *didymobotrya*, *Hakea pandanicarpa* subsp. *crassifolia* Common – *Banksia elderiana**, *B. erythrocephala* var. *erythrocephala*, *B. pallida*, *Beaufortia schaueri*, *Isopogon* sp. Newdegate Other – *Thryptomene urceolaris*
Low shrubs:	Dominant – *Verticordia chrysantha*, *V. eriocephala*, *V. roei* subsp. *roei* Common – *Calytrix* spp., *Lysinema pentapetalum*
Perennial grasses:	Dominant – rarely present as a recognisable stratum Other – *Triodia scariosa*
Other plant forms:	Common – *Lepidosperma* spp. (sedge) Occasional – *Xanthorrhoea nana* (perennial tree-like monocot)

* Also known from Newbey and Hnatiuk (1985, 1988); Newbey et al. (1995)

Priority flora

Calytrix creswellii (Priority 3) was recorded at one site.

Ecological disturbance

Grazing is not a major threat because vegetation is unattractive to livestock. This is a fire-prone habitat which shows similar response to burning as Sandplain heathland (SAHE, #39), Sandplain close mixed shrubland (SCMS, #40) and Sand sheet mallee heath (SAMH, #41). Structural changes are more likely than changes in species composition.

Gradational associations

PINH transitions into SAHE or SAMH as *Callitris* spp. become less dominant, and soils become sandier and deeper. PINH may be replaced by SCMS where the tall shrub stratum increases in density and dominance. In the north, PINH transitions into Plain native pine, acacia woodland (PINW, #46) as acacias begin to dominate the tall shrub stratum and heathland is replaced by spinifex.

Land systems

PINH is a major habitat type in the Newdegate land system and a minor habitat type in the Bannar, Hann, Hyden and Joseph land systems.

Callitris preissii (Rottnest Island pine) woodland over a myrtaceous–proteaceous heathland in the Newdegate land system

Uncommon habitat in the Plains transitional to sandplain habitat group

46 Plain native pine, acacia woodland (PINW)

Sampling

1 inventory site, 3 traverse points

General information

PINW was first described in the Sandstone, Yalgoo and Paynes Find area survey (Payne et al. 1998b). It is named after *Callitris columellaris* (white Cypress pine). In the southern Goldfields, PINW is uncommon, associated with near-level sandplains in the north-west. It is similar to Plain native pine heathland (PINH, #45), particularly in the upper strata, but PINW is considered a different association because the heathland species are replaced by acacias. It commonly occurs on Yellow–brown deep sandy duplex soil within sandplains.

Physiognomy and composition of vegetation

PINW occurs as a scattered to moderately close (15–25% PFC), low (<8 m) woodland or tall shrubland, reflecting the dominance of *Callitris columellaris* or acacias, respectively. Acacias include *A. burkittii* (sandhill wattle), *A. nyssophylla*, *A. ramulosa* (horse mulga) or *A. resinimarginea*. Trees may be present and infrequently dominate the upper stratum. Other tall shrubs are regularly present as scattered individuals, including *Alyxia buxifolia* (dysentery bush) and *Santalum spicatum* (sandalwood). The mid and low shrub strata are generally present but subordinate, and typically include *Enchylaena tomentosa* (ruby saltbush), *Homalocalyx thryptomenoides*, *Maireana triptera* (three-winged bluebush), *Olearia* spp., *Phebalium canaliculatum*, *Ptilotus* spp., *Scaevola spinescens* (currant bush) and *Westringia cephalantha* var. *cephalantha*. *Triodia scariosa* (spinifex) is the most common perennial grass, with infrequent *Austrostipa elegantissima* (feather speargrass) often associated with bush clumps. The perennial herb *Dianella revoluta* (blueberry lily) is often present.

Ecological disturbance

PINW is generally not preferred by livestock and has few palatable perennial shrubs. Signs of grazing impact are not obvious as a result of the overwhelming presence of largely unpalatable shrubs and the predominance of mostly inaccessible foliage on tall shrubs and trees. *Enchylaena tomentosa* and various *Maireana* spp. may decrease with grazing pressure but are rarely conspicuous in ungrazed areas. Substantial (unpalatable) shrub coverage and sandy soils reduce the likelihood of erosion problems.

Gradational associations

As the abundance of *Callitris columellaris* diminishes and soils become deeper and coarser, PINW transitions into other sandy habitat types, such as Sandplain heathland (SAHE, #39) and Sandplain close mixed shrubland (SCMS, #40). It also transitions downslope from sandy rises into habitat types such as Plain York gum, acacia woodland (PYAW, #44).

Land systems

PINW is a minor habitat type in the Bannar, Joseph and Manning land systems.

Callitris columellaris (white Cypress pine) woodland with scattered eucalypts and a mid shrub stratum dominated by acacias over *Triodia scariosa* (spinifex) on a Yellow–brown deep sandy duplex soil in the Manning land system

G Sheetwash hardpan plain shrubland or woodland habitats

These habitat types are dominated by acacia shrubland and woodland and are common throughout the semi-arid to arid rangelands of WA. In the southern Goldfields, they are mainly restricted to the north. Aside from a few outlying populations of *Acacia aneura* (mulga) near Lake Lefroy, these habitat types largely represent the southerly extent of the Eremaean Botanical Province (Beard 1990) and Murchison bioregion (Environment Australia 2000). While *Acacia aneura* dominates most of these habitat types, other acacias are more prominent approaching the South-western Interzone and Coolgardie bioregion. These include *A. burkittii* (sandhill wattle), *A. hemiteles* (tan wattle) and *A. ramulosa* var. *ramulosa*.

The habitat types on hardpan plains represent transitional sheetwash areas between erosional areas upslope and depositional areas downslope (for example, lake country). Two habitat types represent drainage tracts or areas subjected to more concentrated run-on within or through the sheetwash plains. Soils tend to be Red–brown hardpan shallow loam and loamy variants with deeper or shallower hardpan, and occur on broad, near-level plains subject to intermittent sheet flow and flooding. Cryptogamic crusts are common and help protect soil surfaces from erosion during rainfall events and overland flow. Landform flatness also contributes to soil stability by minimising the energy of flowing water and limiting downslope movement of soil particles subjected to raindrop impact. Retention of litter and nutrients by obstacles that hinder overland flow is an important process that contributes to resource redistribution to mosaics of fertile patches between water-shedding, resource-poor interpatches (Hacker 1979; Tongway et al. 1989; Tongway and Ludwig 1990, 1997; Tongway 1994).

Major human-induced modifications have been caused by pastoral grazing (mainly sheep) and localised cutting of mulga for firewood, building and fencing for the pastoral and mining industries. Pringle et al. (1994) found where regeneration of mulga was not successful, the understorey was frequently impoverished, demonstrating the influence of mulga on the distribution of lower-stratum shrubs. The reason for this apparent spatial association has not been conclusively defined, although water and resource capture and recycling processes may play a significant role. Mulga debris and leaf litter aids seed entrapment and provides sheltered niches with favourable water and temperature regimes for germination and establishment.

Observations by Payne et al. (1998b) indicate these habitat types are resilient and can recover from degradation caused by excessive stocking if seed sources remain. In these cases, the only management intervention required is destocking. This resilience is partly due to the inherent stability of the soil and the flat landscape.

47 Hardpan plain mulga shrubland (HPMS)

Sampling

11 inventory sites, 63 traverse points

General information

Across the arid zone of WA, HPMS is one of the most extensive habitat types (Wilcox and McKinnon 1972; Payne et al. 1988; Curry et al. 1994; Pringle et al. 1994; Payne et al. 1998b). In the southern Goldfields, HPMS is mostly restricted to the north, becoming subordinate in extent to Plain eucalypt (mallee), acacia woodland (PEAW, #43), which largely replaces HPMS in the South-western Interzone (Beard 1990) and Coolgardie bioregion (Environment Australia 2000). It occupies transitional plains between uplands and salt lake systems. These sheetwash plains, typically with slopes less than 1%, are subject to low energy sheet flows after major rainfall events. Soils characteristically have hardpans (red–brown, siliceous and sometimes calcrete or granite) at shallow depth (<30 to 70 cm) and often have a loamy texture, but sometimes sandy surfaces. The most common soil is a Red–brown hardpan shallow loam. When the habitat is in good condition, the soils often have a well-developed cryptogamic crust.

Physiognomy and composition of vegetation

HPMS occurs as a scattered to closed (>10% PFC), low (<10 m) woodland or tall shrubland, typically dominated by *Acacia aneura* (mulga), with well-developed mid and low shrub strata. Compared to the north-eastern Goldfields and Sandstone, Yalgoo and Paynes Find areas to the north, the cover is slightly higher, which may correlate with the regularity and amount of rainfall throughout the year in these southern latitudes.

The dominant and common species by strata:

Trees:	Dominant – *Acacia aneura*
	Others – *Brachychiton gregorii*, *Casuarina pauper*
Mallees:	Dominant – rarely present other than as emergents
	Others – *Eucalyptus concinna*, *E. loxophleba* subsp. *lissophloia*
Tall shrubs:	Dominant – *Acacia aneura*
	Common – *Acacia burkittii*, *A. ramulosa* var. *ramulosa*, *A. tetragonophylla*
	Others – *Acacia ramulosa*, *Eremophila alternifolia*, *Santalum spicatum*
Mid shrubs:	Dominant – variable; often *Eremophila* spp., *Senna* spp.
	Common – *Dodonaea lobulata*, *Eremophila forrestii* subsp. *forrestii*, *E. granitica*, *E. latrobei* (KD), *Scaevola spinescens* (KD), *Senna artemisioides*, *S. artemisioides* subsp. *filifolia* (KI), *Sida calyxhymenia* (KD)
	Other – *Eremophila clarkei*
Low shrubs:	Dominant – *Ptilotus obovatus*
	Common – *Maireana triptera*, *Solanum lasiophyllum*
	Others – *Enchylaena tomentosa* (KD), *Rhagodia drummondii* (KD)
Perennial grasses:	Dominant – not present as a recognisable stratum
	Others – *Austrostipa elegantissima* (KD), *A. scabra*, *Monachather paradoxus* (KD)
Other plant forms:	Common – *Leichhardtia australis* (climber)
	Occasional – *Amyema fitzgeraldii* (mistletoe)

Ecological disturbance

Mulga communities are critically dependent on mechanisms that control resource capture and nutrient cycling (Tongway et al. 1989; Tongway and Ludwig 1990, 1997; Tongway 1994). HPMS is particularly vulnerable to disturbance, such as drought, fire, grazing and poorly located infrastructure (roads, fencelines), which cause the breakdown and loss of vegetative or other biological features responsible for intercepting, regulating, conserving and recycling resources. Disrupted hydrological processes can adversely affect soil moisture availability, reducing the edaphic and habitat conditions suitable for recruitment and survival, and resulting in permanent changes in physiognomy and composition.

Mulga deaths are often attributable to a combination of age, moisture stress and/or insect attack, or more singular catastrophic events, such as fire or hailstorm. *Acacia aneura* is fire sensitive and rarely survives if the entire canopy is burned (Hodgkinson and Griffin 1982;

Williams 2002; Wright and Clarke 2007). However, mulga shrubland does not burn readily, especially where closed canopies restrict understorey development or where mulga groves are separated by large, bare intergroves impeding fire spread. Being an obligate seeder, mulga can regenerate prolifically from seed after fire, though fruit production is dependent on consecutive, substantial interseasonal rainfall (Preece 1971; Friedel et al. 1993) and requires 5–15 years to reach maturity (Williams 2002). Where mulga communities are adjacent to fire-prone landscapes, *A. aneura* is vulnerable to seedbank exhaustion if fire intervals become less than 10–15 years because fewer individuals reach maturity (Williams 2002; Nicholas et al. 2009).

Grazing ecology was investigated in some detail in the Murchison River catchment (Curry et al. 1994) and north-eastern Goldfields (Pringle et al. 1994) rangeland surveys. A combination of low density of palatable perennial shrubs and easily accessible fresh water sources for livestock has resulted in widespread modification of floristic composition. Grazing reduces the density and variety of palatable understorey species – such as *Austrostipa elegantissima* (feather speargrass), *Enchylaena tomentosa* (ruby saltbush), *Eremophila latrobei* (warty fuchsia bush), *Monachather paradoxus* (broad-leaved wanderrie grass), *Ptilotus obovatus* (cotton bush), *Rhagodia drummondii* (lake-fringe rhagodia), *Scaevola spinescens* (currant bush) and *Sida calyxhymenia* (tall sida) – which may result in more unpalatable plants, such as *Eremophila* and *Senna* species. Palatable low shrubs are preferentially removed from open areas rather than from under trees and groves (Hacker 1979). The overstorey is rarely adversely affected by grazing, except in extremely degraded situations where herbivory results in disrupted resource capture mechanisms and impeded water infiltration.

Gradational associations

HPMS transitions upslope into Sandy granitic acacia shrubland (SGRS, #11) as the density of mulga decreases and soils become shallower in response to nearby granitic outcrop. HPMS transitions into Hardpan plain mulga shrubland with scattered chenopods (HMCS, #48) where chenopod frequency in the understorey has increased. Where mallees begin to co-dominate the upper strata, HPMS transitions with, and in the south is eventually replaced by, Plain eucalypt (mallee), acacia woodland (PEAW, #43).

Land systems

HPMS a major habitat type in the Helag, Kirgella and Yowie land systems and minor habitat type in the Bandy, Gransal and Illaara land systems.

Acacia aneura (mulga) woodland in the Bandy land system

48 Hardpan plain mulga shrubland with scattered chenopods (HMCS)

Sampling

2 inventory sites, 10 traverse points

General information

HMCS was described in the north-eastern Goldfields (Pringle et al. 1994) and the Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b) surveys. It generally occurs below uplands on alluvial fans receiving nutrient-rich run-on, and on gently inclined sheetwash plains on Red shallow loamy duplex on hardpan soils. It occurs infrequently and is mainly restricted to the north of the survey.

Physiognomy and composition of vegetation

HMCS occurs as a scattered (>10–20% PFC) tall shrubland or occasional low woodland, dominated by *Acacia aneura* (mulga), with a well-developed low shrub stratum in which Chenopodiaceae species are conspicuous. The mid shrub layer is less developed. Trees are a very minor component and perennial grasses are generally absent.

The dominant and common species by strata:

Trees:	Dominant – occasionally *Acacia aneura* Others – *Casuarina pauper*, *Eucalyptus salubris*
Tall shrubs:	Dominant – *Acacia aneura* Common – *Acacia burkittii*, *A. hemiteles*, *A. tetragonophylla* Others – *Eremophila alternifolia*, *Exocarpos aphyllus*, *Hakea preissii* (KI)
Mid shrubs:	Dominant – variable Common – *Dodonaea lobulata*, *Eremophila decipiens*, *E. latrobei* (KD), *Maireana pyramidata*, *Scaevola spinescens* (KD), *Senna artemisioides* subsp. *filifolia* (KI)
Low shrubs:	Dominant – *Maireana triptera* Common – *Atriplex bunburyana* (KD), *Ptilotus obovatus*, *Scaevola spinescens* (KD), *Solanum lasiophyllum* Others – *Enchylaena tomentosa* (KD), *Frankenia spp.*, *Rhagodia* spp., *Solanum lasiophyllum*
Other plant forms:	Common – *Leichhardtia australis* (climber)

Acacia burkittii (sandhill wattle) tall shrubland with scattered *Acacia aneura* (mulga) and *Atriplex stipitata* (kidney saltbush) on an alluvial fan in the Gundockerta land system

Ecological disturbance

Grazing patterns relevant to other chenopod shrubland habitat types, such as Plain mixed halophyte shrubland (PXHS, #70), apply to HMCS. Grazing impact can best be judged by the abundance and diversity of palatable low shrubs beneath the mulga overstorey. The natural scarcity of palatable species, when combined with reliable fresh water sources for livestock, has resulted in the chenopod component of many areas being replaced by *Maireana triptera* (three-winged bluebush) or completely eliminated, leaving the vegetation resembling the less valuable, but more extensive, hardpan mulga plains vegetation of Hardpan plain mulga shrubland (HPMS, #47). When highly palatable decreasers, such as *Atriplex bunburyana* (silver saltbush) and *Enchylaena tomentosa* (ruby saltbush), are well represented in HMCS, the vegetation can be considered in good condition. Other, more tolerant, palatable species include *Maireana pyramidata* (sago bush), *Rhagodia* spp. and *Scaevola spinescens* (currant bush). *Ptilotus obovatus* (cotton bush), while palatable, responds to seasonal conditions as much as grazing pressure and is not as reliable an indicator of condition in this habitat.

Because of the slight gradients associated with upland environments, and when near drainage tracts or alluvial fans, overgrazing leaves duplex soils susceptible to erosion. In these areas, accelerated erosion problems, such as micro-terracing and gullying, may lead to vegetation condition decline as water starvation causes mulga deaths. Unpalatable species, such as *Hakea preissii* (needle bush) and *Senna artemisioides* subsp. *filifolia* (desert cassia), may proliferate in such conditions.

Gradational associations

HMCS usually has clearly defined boundaries with adjacent upslope habitat types, defined by the extent of the alluvial fan. Downslope, HMCS often transitions into HPMS where soils are usually shallower, have poorer profile development and support a much sparser, non-halophytic shrub understorey. Degraded HMCS may also resemble HPMS when the chenopod understorey is significantly reduced, with soil degradation a possible indicator between degraded HMCS and more inherently stable communities.

Land systems

HMCS is a minor habitat type in the Bunyip, Carnegie, Gransal, Gundockerta, Helag, Kanowna and Moriarty land systems.

49 Drainage tract acacia shrubland (DRAS)

Sampling

3 inventory sites, 61 traverse points

General information

DRAS was described in the north-eastern Goldfields survey (Pringle et al. 1994) as Drainage mulga shrubland (DRMS). It was redescribed in the Sandstone, Yalgoo and Paynes Find area survey (Payne et al. 1998b) as DRAS to recognise the prominence of acacias other than *Acacia aneura* (mulga). It occurs in slightly lower sectors of broad sheetwash plains which are accordingly subjected to more concentrated run-on. Soils are variable, but generally are heavier textured than adjacent sheetwash plains and usually have a hardpan at depth.

Physiognomy and composition of vegetation

DRAS ranges from scattered to close (15–50% PFC) tall acacia shrubland, sometimes low woodland, with understorey development inversely related to upper storey cover. Commonly it has a moderately close to close (>20–50% PFC) upper storey and a poorly developed understorey. Eucalypts become more common to the south. Perennial grasses are a minor component and are rarely present as a recognisable stratum.

The dominant and common species by strata:

Trees:	Dominant – *Acacia aneura* Common – *Eucalyptus salubris* Other – *Casuarina pauper*
Mallees:	Dominant – rarely present other than as emergents Others – *Eucalyptus gracilis*, *E. oleosa*
Tall shrubs:	Dominant – *Acacia* spp., often *A. burkittii*, *A. tetragonophylla* Common – *Acacia aneura*, *A. ramulosa* var. *ramulosa*, *Exocarpos aphyllus*, *Melaleuca hamata* Others – *Acacia acuminata*, *Eremophila interstans* subsp. *virgata*, *Santalum acuminatum*, *S. spicatum*
Mid shrubs:	Dominant – variable; often *Acacia* spp., *Eremophila* spp. Common – *Acacia hemiteles*, *A. tetragonophylla*, *Dodonaea lobulata*, *Eremophila granitica*, *Scaevola spinescens*, *Senna artemisioides* subsp. *filifolia*, *Sida calyxhymenia* (KD)
Low shrubs:	Dominant – variable; often *Ptilotus obovatus* Common – *Grevillea acuaria*, *Rhagodia drummondii* (KD), *Scaevola spinescens* Other – *Teucrium teucriiflorum* (KD)
Perennial grasses:	Dominant – rarely present as a recognisable stratum Common – *Austrostipa elegantissima* Others – *Austrostipa scabra*, *Eragrostis dielsii*
Other plant forms:	Occasional – *Amyema* spp. (mistletoes), *Dianella revoluta* (perennial herb)

Ecological disturbance

The understorey is highly variable, however, some palatable shrubs – such as *Ptilotus obovatus* (cotton bush), *Rhagodia drummondii* (lake-fringe rhagodia) and *Sida calyxhymenia* (tall sida) – are expected. Since the palatable understorey shrubs are usually a minor component of this habitat type, grazing impacts rarely cause major problems.

Gradational associations

DRAS transitions out of drainage lines into the surrounding habitats through which the drainage tracts flow. Most often, it transitions into Plain eucalypt (mallee), acacia woodland (PEAW, # 43) or Greenstone hill acacia shrubland (GHAS, #1). With the southern transition from the Eremaean Botanical Province (Beard 1990) and Murchison bioregion (Environment Australia 2000) to the South-western Interzone and Coolgardie bioregion, eucalypts become more common and DRAS is replaced by Drainage tract eucalypt woodland (DREW, #61).

Land systems

DRAS is recorded in many land systems in the survey and is characteristic of drainage through sheetwash plains. It is also common where drainage tracts flow through or are near habitats dominated by acacia shrublands, such as in the Gransal, Jaurdi and Norie land systems.

50 Drainage tract acacia shrubland or woodland with chenopod understorey (DACS)

Sampling

DACS was not sampled during this survey but was present and observed at 21 traverse points

General information

DACS was first described in the north-eastern Goldfields survey (Pringle et al. 1994) as Mulga drainage line shrubland with chenopod understorey (DMCS). It was redescribed in the Sandstone, Yalgoo and Paynes Find area survey (Payne et al. 1998b) as DACS to recognise the prominence of other acacias besides *Acacia aneura* (mulga). It is not extensive, occurring infrequently throughout the north-east of the survey in association with drainage tracts flowing from uplands, through sheetwash and alluvial plains, towards salt lakes. It is typically fringed by chenopod low shrubland on plains with duplex soils. DACS usually has deeper, sometimes heavier textured, soils than the adjacent plains, and can be underlain by hardpan.

Physiognomy and composition of vegetation

DACS varies considerably because the structural development in the overstorey ranges from a scattered to close (>10–50% PFC) shrubland. The floristic composition is common to many other habitat types and consists of a mix of species from an array of non-halophytic and halophytic associations. The tall shrub stratum, and occasionally the tree stratum, are frequently dominated by *Acacia aneura* (mulga), *A. burkittii* (sandhill wattle) and/or *A. tetragonophylla* (curara). Where the upper strata are sparse, the lower shrub stratum may dominate. Mid shrubs and perennial grasses are typically scattered.

The dominant and common species by strata:

Trees:	Dominant – *Acacia aneura*
	Others – *Casuarina pauper*, *Eucalyptus salubris*, *Pittosporum angustifolium*
Tall shrubs:	Dominant – *Acacia* spp., often *A. burkittii*, *A. tetragonophylla*
	Common – *Acacia aneura*, *A. burkittii*, *A. tetragonophylla*, *Hakea preissii* (KI)
	Other – *Santalum spicatum*
Mid shrubs:	Dominant – variable when present
	Common – *Acacia hemiteles* (KI), *Atriplex nummularia* subsp. *spathulata*, *Maireana pyramidata*, *Senna artemisioides* subsp. *filifolia*, *Sida calyxhymenia* (KD)
Low shrubs:	Dominant – variable
	Common – *Atriplex bunburyana* (KD), *A. vesicaria* (KD), *Enchylaena tomentosa* (KD), *Maireana pyramidata*, *Ptilotus obovatus*, *Rhagodia drummondii* (KD), *Scaevola spinescens*
	Others – *Maireana triptera* (KI), *Solanum lasiophyllum*, *S. orbiculatum* (KI)
Perennial grasses:	Dominant – rarely present as a recognisable stratum
	Common – *Austrostipa elegantissima*
	Others – *Austrostipa scabra*, *Eragrostis dielsii*
Other plant forms:	Occasional – *Amyema* spp. (mistletoes), *Leichhardtia australis* (climber)

Ecological disturbance

Palatable understorey species – including *Atriplex bunburyana* (silver saltbush), *A. vesicaria* (bladder saltbush), *Enchylaena tomentosa* (ruby saltbush) and *Rhagodia drummondii* (lake-fringe rhagodia) – can be eliminated by sustained heavy grazing. These species can then be replaced by less palatable species, such as *Maireana triptera* (three-winged bluebush), and invasive species, such as *Acacia hemiteles* (tan wattle), *Hakea preissii* (needle bush) and *Solanum orbiculatum* (wild tomato).

Gradational associations

The overstorey is usually confined to drainage tracts, while the understorey contains species in common with the adjacent chenopod shrubland. With the southern transition from the Eremaean Botanical Province (Beard 1990) and Murchison bioregion (Environment Australia 2000) to the South-western Interzone and Coolgardie bioregion, DACS is replaced by Drainage tract eucalypt woodland (DREW, #61) as eucalypts increase in prominence in the overstorey of drainage tracts.

Land systems

DACS is patchily distributed through the north-east of the survey and infrequent in many land systems, particularly where concentrated drainage tracts flow through chenopod-dominated plains (e.g. Gundockerta land system).

H Sheetwash plain woodland habitats

This group of habitat types occurs on sheetwash plains and is characterised by eucalypt woodlands. Despite the topographically subdued nature of the landscape, the variation in the physiognomy and composition of vegetation communities in the Great Western Woodlands is considerably influenced by topographic position and associated edaphic conditions. This is especially relevant to these eucalypt woodlands. While eucalypt associations do occur on the uppermost landscapes of topographic catena sequences, they are most common in the lower landscapes, such as sheetwash plains (this habitat group H) and alluvial plains (habitat group I: Depositional plain woodland over shrubland habitats), where they dominate as woodlands.

In the Great Western Woodlands, eucalypts are reliable indicators of broad soil characteristics, though subtle soil changes can contribute to intermixed associations or graduated species replacement. Following are some of the more common eucalypt associations. *Eucalyptus transcontinentalis* (redwood) tends to occur on red loamy soil associated with granitic rocks, and occasionally it occurs with other species, such as *E. eremophila* (tall sand mallee), as the sand content increases. *E. oleosa* subsp. *oleosa* (giant mallee) tends to dominate with a variety of other species, such as *E. urna* and *E. dundasii* (Dundas blackbutt) in the south of the survey and is often associated with Calcareous loamy earth or Calcareous shallow loam soils. *E. salmonophloia* (salmon gum) and *E. lesouefii* (Goldfields blackbutt) are commonly associated with *Maireana sedifolia* (pearl bluebush) on Shallow calcareous loam soil associated with lower footslopes and very gently undulating plains. *E. salmonophloia* and *E. salubris* (gimlet) are associated with *Atriplex* (saltbush) species on alluvial plains with clay loams. On heavy-textured clay soils, *E. salubris* is often solely dominant, though in the south it may be locally replaced by other Contortae (gimlets), *E. diptera* and *E. terebra* (Brooker and Kleinig 2001). In the west and south-west of the survey, in landscapes adjacent to lake country with soils rich in calcium carbonate, *E. salmonophloia* may be co-dominant with or replaced by *E. longicornis* (red morrel) and/or *E. melanoxylon* (black morrel).

Some gradational transitions observed in the southern Goldfields between various eucalypt communities appeared to be on similar soil types. Such differences could be a feature of subtler soil conditions than were assessed for, such as water availability, nutrients, or soil factors at greater than 1 m depth. Elsewhere, natural and/or anthropogenic disturbance mechanisms capable of affecting floristic composition and structure have made it difficult to differentiate between where some associations occur within successional expressions or a post-transition vegetation state where a threshold has been crossed.

Many of the eucalypt woodlands have been affected and modified by disturbance across a variety of scales. These include regional climate change impacts (Prober et al. 2012), changes from traditional burning practices by indigenous people (Prober et al. 2013) to landscape-scale wildfires (Yates et al. 1994; O'Donnell et al. 2011b, 2014), grazing (Burnside 1985; Yates et al. 2000) and infrastructure effects (Burnside 1985; Raiter et al. 2017, 2018), through to local-scale, commonplace, natural forms of disturbance such as flooding, hail and wind storms (Yates et al. 1994).

Wood harvesting had a significant impact on the eucalypt and, to a lesser extent, *Acacia aneura* (mulga) woodlands of the southern Goldfields. With gold discoveries in Coolgardie (1892), Kalgoorlie (1893) and Kambalda (1893), the ensuing gold rush resulted in extensive clear-felling to supply mining timber, railway sleepers and fuel for steam boilers, water pipeline pumping stations, locomotives and general domestic supply (Burnside 1985; Keally 1991; Bunbury 1997). In 1918, regulations were introduced to create timber reserves in response to concern for the diminishing reserves of accessible timber and denudation around towns, as well as to protect wood supplies for mining and pastoral pursuits. With wider adoption of fossil fuels in the 1940s, woodcutting for industrial fuels in the Goldfields decreased. The woodlines had closed by the 1960s (Burnside 1985).

Melaleuca groves in an area formerly logged by woodcutters, with remnant stumps cut with axes are still visible in the foreground

Old railway sleepers on an abandoned line that once supplied wood to the mining towns and pumping stations of the region

With the cessation of industrialised harvesting in most places, the woodlands have successfully regenerated from coppice and seed. Apart from some areas that remain treeless or only have a few scattered individuals of *E. salmonophloia*, it is hard to differentiate between regrowth and unlogged woodlands. Such was the widespread and extreme nature of the logging, which included the use of gelignite to remove stumps (Bunbury 1997), in conjunction with wildfires (Fitzgerald 1976; Burnside 1985) and voracious termite activity, the on-ground evidence of remnant felled large trees from this era is scarce. The successful, natural regeneration in clear-felled woodlands is likely due to the apparent propensity of *E. salmonophloia* to respond favourably to disturbances (Yates et al. 1994). With soil water being the salient factor limiting growth of *E. salmonophloia* (Yates et al. 2000), the removal of resource competition by mature trees assists germination and early survival of juveniles, especially if regeneration corresponds with favourable seasonal conditions (Yates et al. 1994).

Within the Great Western Woodlands, many eucalypt-dominated woodland communities are sensitive to fire. *E. salubris* is particularly susceptible to fire, with complete canopy scorching capable of killing trees (Gosper et al. 2013a). *E. salmonophloia* is able to resprout following fire because of its slightly thicker bark (Gosper et al. 2013a and references therein). Despite sensitivity to fire when compared to other habitat types in the Great Western Woodlands (e.g. Sandplain shrubland habitats), modelling suggests these eucalypt woodlands can have long fire-return intervals of many hundreds of years (O'Donnell et al. 2011a). In mature eucalypt woodlands, the reduced likelihood of burning is in part due to the height, openness and structure of the tree canopy, in addition to the scattered character and height of the understorey, discontinuous litter coverage and large patches of bare ground. The spatial distribution of landscape units, such as salt lakes, affects landscape connectivity and acts as barriers to fire. O'Donnell et al. (2011a) found that eucalypt woodlands in protected landscape locations with large (greater than 5 km^2), well-connected fire barriers tended to have extremely long fire-return intervals.

However, the resurgence of tussock grasses through the southern Goldfields may result in changes to woodland fire intervals and intensities. Grasses are becoming more prominent. On pastoral leases, *Austrostipa elegantissima* (feather speargrass) and *A. scabra* (speargrass) are becoming more frequent in response to reduced grazing pressure since the reduction in sheep and goat numbers since the early 2000s. *Cenchrus ciliaris* (buffel grass) is also becoming more common as changing climatic conditions favour range extension.

With continuing tussock grass re-establishment improving spatial connectivity within eucalypt woodlands, it is probable climatic variations could produce similar conditions to those preceding the devastating 1974–75 and 1975–76 fires in the Kalgoorlie–Nullarbor districts (Fitzgerald 1976; Lay 1976; Burnside 1985). Vegetation communities were extensively burned after consistent wet seasons stimulated prolific grass and ephemeral herb growth, which was immediately followed by very hot, dry conditions which produced continuous, highly flammable fuel loads. Spatial and climatic reviews (O'Donnell et al. 2011b, 2014) show that when interannual variation and extreme climatic conditions influence fuel accumulation and flammability, the fuel conditions that usually constrain fire spread are overcome (O'Donnell et al. 2011a). The repeat of such events can be expected with major consequences for communities with low fire tolerance. With fire-sensitive woodlands, such as those dominated by *E. salubris*, requiring greater than 200-year intervals between fires to reach floristic maturity (Gosper et al. 2013b), the increasing fire frequency is likely to significantly affect species composition.

51 Colluvial slope eucalypt woodland over non-halophytic shrubland (CEWS)

Sampling

21 inventory sites, 10 traverse points

General information

CEWS is described for the first time. It is a woodland community common to the Youanmi South Zone. CEWS occurs on gently inclined hillslopes, footslopes and low rises associated with the ferruginous, greenstone hills in the west of the survey. It is also common to the very gently to gently inclined colluvial slopes and sheetwash plains adjacent to the greenstone hills and granitic landforms throughout the Youanmi South Zone.

The low hills predominantly consist of greenstones, but are often interlayered with metasedimentary rocks and minor BIF. Ferruginous duricrust is common. The hillslopes and footslopes often have variable mantles, ranging from dense to sparse, though outcrop is rarely present. Soils are variable. The dominant soil type is Alkaline red shallow loamy duplex, with common Calcareous loamy earth. Other less common and shallower soils are Red shallow loamy duplex and Calcareous shallow loam. The soils of the colluvial slopes and sheetwash plains are often shallow and characteristically contain coarse fragments, commonly ironstone gravel or basalt stones. Common soils are Loamy gravel and Shallow loamy gravel with ferruginous concretions and hardpans, and Calcareous shallow loam with basalt at depth. A mantle may be present on colluvial slopes, particularly when proximal to upland landforms or protruding granites. Elsewhere, the sheetwash plains commonly lack a surface mantle. Colluvial slopes and sheetwash plain soils are variably influenced by underlying substrate and parent material.

CEWS is similar to Plain eucalypt, eremophila woodland (PEEW, #59) but it is considered different because it occupies inclined slopes rather than level plains. The physiognomy and composition of vegetation also differs slightly, with CEWS characterised by a well-developed tall shrub stratum rather than the mid and low shrub strata. While the upper canopies can have similar eucalypt species, the shrub layers of the CEWS understorey are variably dominated by mixed non-halophytic shrubs and not solely by *Eremophila* species, as in PEEW.

Physiognomy and composition of vegetation

CEWS occurs as a scattered to moderately close (15–30% PFC) eucalypt woodland, characterised by a well-developed, moderately close to close (>20–50% PFC) tall shrubland. In some locations, closed (>50% PFC) stands of single-stemmed eucalypts occur where prolific regeneration from seed has occurred. This habitat does not support an obvious Chenopodiaceae complex, though a few chenopods may be present among tree-based clumps. Perennial grasses are usually confined among shrubs.

While the CEWS structure is consistent, variations in geology and topographic location result in the vegetation composition of the upper stratum varying, with different species of eucalypts occurring over similar understorey. On the upper colluvial slopes with shallower soils, *Eucalyptus capillosa* (inland wandoo), *E. clelandiorum* (Cleland's blackbutt) and *E. corrugata* (rough-fruited mallee) occur most often. On the lower colluvial slopes, *E. celastroides* subsp. *celastroides* (mirret), *E. gracilis* (white mallee), *E. oleosa* subsp. *oleosa* (giant mallee), *E. salmonophloia* (salmon gum), *E. salubris* (gimlet) and *E. transcontinentalis* (redwood) are most common. *E. longicornis* (red morrel) and *E. urna* are common to both slope classes. Melaleucas frequently dominate the tall and mid shrub strata. Species, such as *Melaleuca pauperiflora* (boree), *M. pauperiflora* subsp. *fastigiata* and *M. sheathiana* (boree) are often present as dense groves, while patches of *M. hamata* scrub may dominate the mid shrub stratum. The low shrub stratum supports a variety of scattered non-halophytic species, with *Olearia muelleri* (Goldfields daisy) and *Scaevola spinescens* (currant bush) being most common.

Eucalyptus longicornis (red morrel) woodland over groves of *Melaleuca pauperiflora* subsp. *fastigiata* on a footslope in the Perilya land system

The dominant and common species by strata:

Trees:	Dominant – variable; mainly *Eucalyptus salubris*, *E. urna*; occasionally *E. capillosa*, *E. clelandiorum*, *E. longicornis*, *E. salmonophloia*, *E. transcontinentalis*
	Common – *Eucalyptus salmonophloia*, *E. salubris*, *E. urna*
	Other – *Eucalyptus corrugata**
Mallees:	Dominant – variable; occasionally *Eucalyptus celastroides* subsp. *celastroides*, *E. celastroides* subsp. *virella*, *E. gracilis*, *E. oleosa* subsp. *oleosa*
Tall shrubs:	Dominant – variable; *Melaleuca* spp.
	Common – *Alyxia buxifolia*, *Eremophila oppositifolia*, *Exocarpos aphyllus*, *Melaleuca pauperiflora*, *M. pauperiflora* subsp. *fastigiata*, *M. sheathiana*, *Santalum acuminatum*
	Others – *Acacia nyssophylla*, *Melaleuca acuminata*, *Santalum spicatum*
Mid shrubs:	Dominant – variable; *Eremophila ionantha*, *Melaleuca hamata*
	Common – *Dodonaea stenozyga*, *Eremophila scoparia*
	Others – *Daviesia* spp., *Senna artemisioides* subsp. *filifolia*
Low shrubs:	Dominant – *Olearia muelleri*, *Scaevola spinescens*
	Common – *Acacia acoma*, *A. erinacea*, *Grevillea acuaria*
	Others – *Eremophila clavata*, *Rhagodia* spp., *Westringia cephalantha* var. *cephalantha*, *Wilsonia humilis*
Perennial grasses:	Dominant – rarely present as a recognisable stratum
	Common – *Austrostipa elegantissima* (KD)
Other plant forms:	Occasional – *Cassytha melantha* (climber)

* Also known from Newbey and Hnatiuk (1985); Newbey et al. (1995)

Priority flora

Melaleuca agathosmoides (Priority 1) was recorded at one site.

Ecological disturbance

There is little evidence that grazing by livestock threatens this habitat. The majority of CEWS occurs outside the pastoral estate and grazing by feral animals has minimal impact because a significant proportion of foliage is unpalatable. Grazing pressure would be concentrated towards the suite of palatable species typically associated with tree-based clumps. Berry-bearing, bird-dispersed, palatable low shrubs, such as *Rhagodia* spp. and *Scaevola spinescens* (currant bush), would likely be sought if grazing was occurring.

With the very long fire intervals of hundreds of years recorded in these woodlands (O'Donnell et al. 2011a; Gosper et al. 2013b), periods of 35 to 120 years between fires are considered to represent an intermediate phase in woodland development (Gosper et al. 2013b). During these intermediate periods between fires, Gosper et al. (2013b) suggest that the variation in overstorey development influences the diversity of the understorey through competition supressing subdominant vegetation. The similarity in the suite of understorey species across habitats is likely because these species – as subsequent colonisers capable of coexisting under the dominant overstorey – have traits to exploit competition as the woodland matures. In addition to the upper tree stratum controlling understorey diversity, the next stratum may also have a similar influence on diversity through competition. As in other fire-sensitive habitat types, the low fire tolerance, and variability in the physiognomy and composition of CEWS is an expression of a particular stage in woodland development since a disturbance event. This is supported by Harvey (2014), who found the low tree *Melaleuca pauperiflora* to be most abundant in *Eucalyptus salubris*-dominated CEWS habitats within the intermediate age range since fire.

Soils are not usually susceptible to accelerated erosion because the density of tall shrubs provides significant protection against rainfall impact and wind, while branch debris and leaf litter reduce surface water flows in habitats with long intervals between fires. However, where vehicle tracks on gradients cause local incision, sheetwash can become disrupted and concentrated down tracks, causing rill erosion or resulting in water starvation of downslope habitats where tracks are perpendicular to flow.

Gradational associations

The ecotone boundary between greenstone and BIF hill crests, and ferruginous hillslopes and upper colluvial slopes, is usually clearly defined and the division between CEWS and habitat types such as Lateritic allocasuarina scrub (LASC, #18) is distinct. Where colluvial slopes merge with the footslopes of granitic uplands or pavements, CEWS transitions into Granitic pediment eucalypt, tall shrub thicket (GETT, #12).

CEWS transitions into Plain eucalypt, eremophila woodland (PEEW, #59) as colluvial slopes level on to broad, valley floors and where melaleuca groves become less conspicuous, while the mid shrub stratum becomes better developed and dominated by eremophilas. In the south-east of the Youanmi South Zone, CEWS may transition into Eucalypt, false bluebush woodland (EFBW, #53) as *Eucalyptus oleosa* subsp. *oleosa* becomes the dominant eucalypt over mid to low shrubland dominated by *Cratystylis conocephala* (false bluebush).

Land systems

CEWS is a major habitat type in the Greenmount, Johnston and Perilya land systems.

52 Plain eucalypt, bluebush woodland (PEBW)

Sampling

17 inventory sites, 652 traverse points

General information

PEBW was recognised as a subtype of Plain eucalypt, chenopod woodland (PECW) in the north-eastern Goldfields (Pringle et al. 1994) and Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b) surveys. PECW was split according to the dominant genus of the understorey: PEBW for bluebushes (*Maireana*) and PESW for saltbushes (*Atriplex*). PEBW was treated as a distinct habitat in the Kambalda survey (Payne et al. 1998a) because of its prominence throughout greenstone-dominated landscapes in the region. Typically, the understoreys of PEBW dominated by *Maireana sedifolia* (pearl bluebush) transition into saltbush-dominated understoreys (PESW) with decreasing gradients towards landforms accumulating heavier-textured alluvial soils. PEBW is commonly associated with lower footslopes and very gently undulating calcareous loamy plains. A mantle is typically absent, but when present, consists of a variable coverage from 10% to 90% of subrounded, fine (2–6 mm) ironstone gravels and/or coarse (2–20 cm), angular to subangular gravels or stones typically of quartz, greenstone or granite. Soils vary according to topography. The dominant soil is Alkaline red shallow loamy duplex, which can grade to deep variants and sandy-surfaced variants (rather than shallow loamy). Calcareous loamy earth soils, sometimes with calcareous concretions, are common.

Physiognomy and composition of vegetation

PEBW occurs as a scattered to moderately close (>10–30% PFC) eucalypt woodland with a well-developed mid to low shrubland dominated by *Maireana sedifolia*. When in good condition, *M. sedifolia* may be co-dominant with *Atriplex vesicaria* (bladder saltbush). The tree stratum consists primarily of very scattered to scattered (>2.5–20% PFC) *Eucalyptus salmonophloia* (salmon gum), growing to 25 m. *E. lesouefii* (Goldfields blackbutt) and *E. salubris* (gimlet) are also often present. *E. oleosa* subsp. *oleosa* (giant mallee) dominates PEBW near Fraser Range. The tall shrub stratum is typically sparse and sometimes non-existent. The low shrub layer is sometimes denser than the tree overstorey, ranging from 10% to 20% PFC. Perennial grasses are patchily distributed.

The dominant and common species by strata:

Trees:	Dominant – *Eucalyptus salmonophloia*; occasionally *E. lesouefii*, *E. salubris*, *E. transcontinentalis*
	Common – *Eucalyptus lesouefii* and *E. salubris* (when other species are dominant)
	Others – *Casuarina pauper*, *Pittosporum angustifolium*
Mallees:	Dominant – rarely present as a recognisable stratum, except *Eucalyptus oleosa* subsp. *oleosa* around footslopes of Fraser Range
	Other – *Eucalyptus celastroides* subsp. *celastroides*
Tall shrubs:	Dominant – rarely present as a recognisable stratum
	Common – *Eremophila scoparia* (KI)
	Others – *Acacia acuminata*, *A. burkittii*, *A. tetragonophylla*, *Dodonaea lobulata* (KI), *Eremophila dempsteri*, *E. interstans* (KI), *E. interstans* subsp. *interstans* (KI), *Exocarpos aphyllus*
Mid shrubs:	Dominant – *Maireana sedifolia*
	Common – *Atriplex nummularia* subsp. *spathulata*, *Eremophila scoparia* (KI), *Senna artemisioides* subsp. *filifolia* (KI)
	Others – *Eremophila decipiens*, *E. deserti*, *E. glabra*, *E. ionantha*
Low shrubs:	Dominant – *Maireana sedifolia*, *Atriplex vesicaria* (KD)
	Common – *Enchylaena tomentosa* (KD), *Maireana tomentosa*, *M. triptera*, *Olearia muelleri*, *Ptilotus obovatus*, *Scaevola spinescens*, *Solanum lasiophyllum*
	Others – *Cratystylis subspinescens*, *Maireana georgei* (KD), *M. pyramidata*, *M. radiata*, *Rhagodia drummondii* (KD)
Perennial grasses:	Dominant – not present as a recognisable stratum
	Others – *Austrostipa elegantissima* (KD), *A. platychaeta* (KD)
Other plant forms:	Common – *Maireana trichoptera* (perennial herb; KD), *Ptilotus exaltatus* (annual herb), *Sclerolaena diacantha* (perennial herb)
	Others – *Leichhardtia australis* (climber), *Roepera* spp., *Sclerolaena* spp.

Ecological disturbance

Grazing has had a significant effect on PEBW habitats by reducing the density and diversity of palatable understorey species up to 3 km from water. The almost sole presence of *Maireana sedifolia* in the understorey reflects previous overgrazing or fire. The most reliable indicator of vegetation condition is the diversity of understorey species. When PEBW is in good condition, *Atriplex vesicaria* and tussocks of the perennial grass *Austrostipa elegantissima* (feather speargrass) occur in spaces between the mounds occupied by *M. sedifolia*, along with a mix of palatable bluebush species, such as *M. georgei* (George's bluebush) and *M. trichoptera* (pink-seeded bluebush). In poor condition, unpalatable increaser species – such as *Dodonaea lobulata* (bead hopbush), *Eremophila scoparia* (broom bush) and *Senna artemisioides* subsp. *filifolia* (desert cassia) – are relatively abundant and *A. vesicaria* is often absent.

Components of PEBW are sensitive to fire. While *E. salmonophloia* and *M. sedifolia* can tolerate mild, ground-level fire, *E. salubris* and *A. vesicaria* are very susceptible and often killed (Graetz and Wilson 1984; Gosper et al. 2013a). Despite sensitivity to fire, PEBW can have many hundreds of fire-free years (O'Donnell et al. 2011a). In mature woodlands, a scattered, low understorey with discontinuous litter coverage and large bare patches is a primary reason for reducing the likelihood of burning, as well as factors such as the height, openness and structure of the tree canopy. However, the frequency and intensity of fires may increase with the ongoing recruitment of tussock grasses (*Austrostipa elegantissima*, *A. scabra*), which have responded to the district-wide reduction in sheep numbers since the early 2000s and changing climate (Stephens 2018). With tussock grasses increasing in prominence through the understorey, the improving spatial connectivity may influence fuel accumulation and flammability, which under certain climatic conditions may have major consequences for species with low fire tolerance.

Eucalyptus salmonophloia (salmon gum) and *E. salubris* (gimlet) woodland over *Maireana sedifolia* (pearl bluebush) on an Alkaline red shallow loamy duplex soil in the Gumland land system

Gradational associations

With increasing gradients towards uplands and rises on stony, shallow soils, PEBW commonly transitions into Greenstone eucalypt, bluebush woodland (GEBW, #27) with *Eucalyptus salmonophloia* replaced by *E. griffithsii* (Griffith's grey gum) and/or *E. lesouefii*. Downslope towards alluvial landforms and heavier-textured soils, PEBW typically transitions into Plain eucalypt, saltbush woodland (PESW, #58) as saltbush dominates the understorey and the eucalypt woodlands become co-dominated or solely dominated by *E. salubris*. PEBW transitions into Plain eucalypt, halophytic woodland (PEHW, #60) in areas beside sluggish drainage tracts and increasing salinity.

In the west, PEBW commonly transitions into Plain eucalypt, eremophila woodland (PEEW, #59), and in the south-east, it transitions into Eucalypt, false bluebush woodland (EFBW, #53). As woodland mosaics transition, variations occur in the species composition of the tree and mallee strata and the understorey. The association of *E. salmonophloia* and *M. sedifolia* is typically replaced by *E. transcontinentalis* (redwood) and *Eremophila scoparia* in PEEW, or *E. oleosa* subsp. *oleosa* (giant mallee) and *Cratystylis conocephala* (false bluebush) in EFBW.

PEBW resembles Calcareous pearl bluebush shrubland (CPBS, #31) to the north of the Coolgardie bioregion (South-western Interzone), which has very scattered *Acacia aneura* (mulga) and *Casuarina pauper* (black oak) tall shrubs and trees instead of eucalypt overstoreys. In the Kambalda survey, Payne et al. (1998a) suggested some CPBS habitats may be a consequence of logging, whereby some PEBW habitats were altered to CPBS with the elimination of the eucalypt overstorey. For various reasons, eucalypt regeneration has been patchy and resulted in some areas returning to PEBW, while others never regained their trees and became CPBS.

Land systems

PEBW is the dominant habitat type in the Woolibar land system, a major habitat type in the Gumland land system and minor habitat type in the Coolgardie, Doney, Kanowna, Moriarty and Yardilla land systems. PEBW features in many land systems at ecotone boundaries where gradients change and the vegetation transitions into adjacent habitat types.

53 Eucalypt, false bluebush woodland (EFBW)

Sampling

19 inventory sites, 143 traverse points

General information

EFBW is described for the first time. It is similar to Eucalypt mixed scrub woodland (EXSW) described in the adjacent WA Nullarbor survey (Waddell et al. 2010). 'False bluebush' is preferred here in recognition of the prominence of *Cratystylis conocephala* in the mid and low shrub strata. EFBW is predominantly found on calcareous loamy plains throughout a significant portion of the south-east of the survey area. Soils are commonly Calcareous loamy earth and Calcareous shallow loam, and often have dense calcareous gravel layers at depth. A mantle may be absent, but when present, it typically consists of a variable coverage from 20% to 90% of rounded, medium to coarse (6–60 mm) calcrete gravels or concretions.

EFBW, Eucalypt, teatree woodland (ETTW, #54) and Dense eucalypt, melaleuca forest (DEMF, #55) form a tripartite mosaic of woodland communities which subtly grade into each other throughout the south-east of the survey in the Dundas, Nanambinia and Salmon Gums Mallee zones, as well as the lower slopes of the Fraser Range Zone.

Physiognomy and composition of vegetation

EFBW occurs as a scattered to moderately close (>10–30% PFC) eucalypt woodland with the mid and low shrub strata dominated by *Cratystylis conocephala* (false bluebush). *Eucalyptus oleosa* subsp. *oleosa* (giant mallee) is the dominant eucalypt, but other common eucalypts include *E. lesouefii* (Goldfields blackbutt), *E. salubris* (gimlet) and *E. urna*. Shrub composition varies though the tall shrub stratum is frequently dominated by *Melaleuca sheathiana* (boree) with *Exocarpos aphyllus* (leafless ballart), *Melaleuca lanceolata* (Rottnest teatree) and *Santalum acuminatum* (quandong) common; with *Atriplex nummularia* subsp. *spathulata* (old man saltbush), *Eremophila scoparia* (broom bush) and *Senna artemisioides* subsp. *filifolia* (desert cassia) featuring commonly in the mid shrub stratum; and *Atriplex vesicaria* (bladder saltbush), *Olearia muelleri* (Goldfields daisy), *Scaevola spinescens* (currant bush) and *Westringia rigida* (stiff westringia) common throughout the lower shrub stratum.

The dominant and common species by strata:

Trees:	Common – *Eucalyptus lesouefii*, *E. salubris*, *E. urna* Other – *Eucalyptus transcontinentalis*
Mallees:	Dominant – *Eucalyptus oleosa* subsp. *oleosa* Others – *Eucalyptus gracilis*, *E. protensa* (in the east around Fraser Range)
Tall shrubs:	Dominant – *Melaleuca sheathiana* Common – *Eremophila scoparia*, *Exocarpos aphyllus*, *Geijera linearifolia*, *Melaleuca lanceolata*, *Santalum acuminatum* Other – *Alyxia buxifolia*
Mid shrubs:	Dominant – *Cratystylis conocephala* Common – *Atriplex nummularia* subsp. *spathulata*, *Eremophila scoparia*, *Senna artemisioides* subsp. *filifolia* Others – *Acacia hemiteles*, *A. merrallii*, *Eremophila caperata*, *E. decipiens*, *E. ionantha*
Low shrubs:	Dominant – *Atriplex vesicaria* (KD), *Cratystylis conocephala*, *Westringia rigida* Common – *Eremophila parvifolia* subsp. *auricampa*, *Maireana pentatropis*, *M. sedifolia*, *M. tomentosa*, *Olearia muelleri*, *Scaevola bursariifolia*, *S. spinescens* Others – *Eremophila oblonga*, *Olearia calcarea* (in the east), *Maireana erioclada*, *Ptilotus obovatus*, *Rhagodia crassifolia* (KD), *R. drummondii* (KD), *Solanum orbiculatum*
Perennial grasses:	Dominant – rarely present as a recognisable stratum Others – *Austrostipa elegantissima*, *A. scabra*, *Triodia scariosa*
Other plant forms:	Common – *Sclerolaena diacantha* (perennial herb)

Eucalyptus oleosa subsp. *oleosa* (giant mallee) woodland over *Cratystylis conocephala* (false bluebush) on a Calcareous loamy earth in the Gumbelt land system

Ecological disturbance

EFBW has not been significantly affected by pastoralism, primarily because of its distribution outside the pastoral estate and the lack of water sources for livestock. The most reliable indication of grazing impact is the diversity and density of palatable low shrubs which are often most numerous among tree clumps. The increase in abundance of unpalatable species – such as *Acacia hemiteles* (tan wattle), *Eremophila scoparia* and *Senna artemisioides* subsp. *filifolia* –

may be a result of rabbits eating the seedlings of palatable shrubs that germinate after fire. Increasing camel populations during extended dry periods may also cause future concern. Susceptibility to fire largely depends on the development of the grass strata and litter accumulation.

Gradational associations

In the north and west of the survey, EFBW commonly transitions into Plain eucalypt, bluebush woodland (PEBW, #52), Plain eucalypt, saltbush woodland (PESW, #58) or Plain eucalypt, eremophila woodland (PEEW, #59) as variations in the understorey between halophytic and non-halophytic shrubs form a mosaic of transitioning understoreys. The dominant association of *E. oleosa* subsp. *oleosa* and *C. conocephala* in EFBW is typically replaced, respectively, by *E. salmonophloia* (salmon gum) and bluebushes (PEBW) in broad alluvial tracts and valley floors, and by *E. salubris* and saltbushes (PESW) in drainage foci as soils become increasingly heavier textured. EFBW transitions into Plain eucalypt, halophytic woodland (PEHW, #60) where the topsoil becomes more saline, and into Mallee, hummock grass woodland (MHGW, #35) where the topsoil becomes sandier.

On the lower footslopes of hills associated with Fraser Range EFBW transitions into *Eucalyptus oleosa*, saltbush woodland (EOSW, #56). In specific areas where *Melaleuca* groves become more contiguous with declining lower understorey, EFBW transitions into Dense eucalypt, melaleuca forest (DEMF, #55).

Towards the northern extremity of the Salmon Gums Mallee Zone, EFBW transitions into Eucalypt, teatree woodland (ETTW, #54) as *Cratystylis conocephala* becomes less conspicuous through the mid and low shrub strata.

Land systems

EFBW is the dominant habitat type in the Dundas, Harms and Yardilla land systems, a major habitat type in the Caiguna, Charlina, Doney, Erayinia, Gumbelt and Noondoonia and a minor habitat type in the Eundynie and Lakeside land systems.

54 Eucalypt, teatree woodland (ETTW)

Sampling

8 inventory sites

General information

ETTW is described for the first time. It is a woodland community common to the south-east of the survey area. ETTW occurs on very gently undulating broad rises to level sheetwash plains associated with the extensive pediplains of the Dundas, Nanambinia and Salmon Gums Mallee zones and the lower slopes of the Fraser Range Zone. With Dense eucalypt, melaleuca forest (DEMF, #55) and Eucalypt, false bluebush woodland (EFBW, #53), it forms a tripartite mosaic of woodland communities which subtly merge throughout these zones. Soils are Calcareous loamy earth, Calcareous gravelly loamy earth, Red loamy earth with calcareous subsoil concretions, and Alkaline red shallow loamy duplex.

ETTW is similar to Eucalypt, false bluebush woodland (EFBW, #53) and Plain eucalypt, eremophila woodland (PEEW, #59), but it is considered different because of its physiognomy and composition. ETTW is characterised by a well-developed tall shrub stratum with moderately developed mid and low shrub strata. While there are similarities with EFBW in the dominant association of the mallees (i.e. *Eucalyptus oleosa* subsp. *oleosa*), ETTW differs from EFBW because *Cratystylis conocephala* (false bluebush) is generally absent in the lower strata of ETTW. When compared against PEEW, ETTW is different in the tree and shrub strata, with *Eucalyptus salmonophloia* (salmon gum) noticeably absent, and although *Eremophila* species are prominent in the mid shrub stratum, they are not dominant.

ETTW is also different from PEEW because of its undulating topography and soil associations. ETTW occurs on gently undulating plains which grade into gently inclined, broad slopes of rolling rises with rounded crests, with soils partially supplied from calcareous loess derived from the Eucla Basin during the upper Neogene and Quaternary (Doepel 1973). Soils are generally calcareous and often display pedogenetic carbonate concretions at depth, with loamy upper soil horizons and clay content increasing with depth. This contrasts with PEEW, which occurs on level plains derived from colluvium and alluvium and dominated by duplex soil profiles, often with alkaline subsoils but lacking the vast accumulation of carbonates.

Description of physiognomy and vegetation composition is limited because fires have affected extensive tracts of this habitat. Consequently, areas burned by relatively recent fires (i.e. within the last 10 years) have regrowth dominated by dense stands of eucalypt saplings, often with no suitable reference material available for collection. Furthermore, data acquisition was restricted by poor access, and further constrained by both wet weather and fires during the survey.

Physiognomy and composition of vegetation

ETTW tends to occur as a mosaic of moderately close to closed (>20% PFC), low (<15 m) tree woodland, which is characterised by moderately close (>20–30% PFC) groves of *Melaleuca* species. Scattered to moderately close (>10–30% PFC) eucalypts dominate the tree stratum, with species dominance subtly changing and intermixing between mosaics. Resprouting further complicates the differentiation between these mosaics in the eucalypts after fire, resulting in physiognomic similarities between burnt woodland and mallee-dominated habitat types. The mid and low shrub strata are variably developed and consist of non-halophytic shrubs. Perennial grasses are sparse.

The dominant and common species by strata:

Trees:	Dominant – variable; occasionally *Eucalyptus assimilans*, *E. cylindrocarpa*, *E. laevis*, *E. lesouefii*
	Common – *Eucalyptus lesouefii* (when other species are dominant)
	Others – *Eucalyptus dundasii*, *E. longicornis**, *E. salubris**, *E. transcontinentalis*, *E. urna*
Mallees:	Dominant – *Eucalyptus oleosa* subsp. *oleosa*; occasionally *E. cylindrocarpa*
	Other – *Eucalyptus eremophila**
Tall shrubs:	Dominant – mainly *Melaleuca sheathiana*; occasionally *M. lanceolata*
	Common – *Alyxia buxifolia*, *Exocarpos aphyllus*, *Melaleuca pauperiflora* subsp. *fastigiata*, *Santalum acuminatum*
Mid shrubs:	Dominant – variable
	Common – *Eremophila decipiens*, *E. ionantha*, *E. scoparia*, *Senna artemisioides* subsp. *filifolia*
	Others – *Beyeria sulcata*, *Cratystylis conocephala*, *Dodonaea stenozyga*
Low shrubs:	Dominant – *Olearia muelleri*, *Scaevola spinescens*
	Common – *Acacia acoma*, *A. camptoclada*, *Halgania andromedifolia*
	Others – *Acacia erinacea*, *Daviesia* spp.

Perennial grasses: Dominant – not present as a recognisable stratum
Others – *Austrostipa elegantissima*, *A. scabra*

* Also known from Beard (1975), Newbey and Hnatiuk (1984)

Ecological disturbance

It is difficult to confidently assess grazing impacts on this habitat's vegetation because the extent of its variability is largely unknown. In most cases, the dominant plants are not particularly palatable or preferred by livestock. Disturbance events affecting Eucalypt, false bluebush woodland (EFBW, #53) are likely to have similar effects on ETTW.

Gradational associations

ETTW transitions into EFBW as *Cratystylis conocephala* (false bluebush) becomes conspicuous through the mid and low shrub strata, and into Dense eucalypt, melaleuca forest (DEMF, #55), as the understorey becomes sparse as *Melaleuca* groves become more contiguous.

The westernmost communities transition into PEEW as *Eucalyptus salmonophloia* frequency increases in the tree stratum with *E. transcontinentalis,* and *Eremophila* species begin to dominate the mid shrub stratum.

With the transition from the southern extent of the Dundas and Nanambinia zones into the Salmon Gums Mallee Zone, – marked by the edaphic change from Calcareous and/or Red loamy earth or Shallow loamy duplex soils to Yellow–brown sandy duplex soils over alkaline subsoil – ETTW transitions into a Eucalypt mallee, melaleuca shrubland (EMMS, #68) and eventually contracts to patches of woodland within an EMMS matrix.

Land systems

ETTW is a major habitat type in the Cowalinya and Frasershear land systems and a minor habitat type in the Charlina, Dundas, Harms and Quartzitehill land systems.

The effect of fire on the structure and composition of the Eucalypt, teatree woodland: left of the track, the woodland is dominated by a dense stand of eucalypt saplings in response to a recent fire (within the last 10 years); right of the track, the vegetation is more structurally mature because it has not been burned as recently

55 Dense eucalypt, melaleuca forest (DEMF)

Subtype: Dundas blackbutt, melaleuca forest (DBMF)

Sampling

DEMF: 6 inventory sites, 6 traverse points

DBMF: 4 inventory sites, 4 traverse points

General information

DEMF is described for the first time. It is a forest community characterised by a very sparse understorey. It occurs in the south-east of the survey area, on very gently undulating to level marine-derived sheetwash plains, in the Dundas, Nanambinia, Salmon Gums Mallee zones and lower slopes and pediplains of the Fraser Range Zone. With Eucalypt, teatree woodland (ETTW, # 54) and Eucalypt, false bluebush woodland (EFBW, #53), it forms a tripartite mosaic of woodland communities which subtly intermix throughout the zones.

A subtype of DEMF is Dundas blackbutt, melaleuca forest (DBMF). While the physiognomy and composition of the DBMF association is similar to DEMF, it is distinguished by the dominance of *Eucalyptus dundasii* (Dundas blackbutt) in the tree stratum. DEMF was treated as the major habitat type and DBMF was used as a component to provide species-specific information in the field, particularly when traversing.

Soils of DEMF and its subtype are typically Calcareous loamy earth or Calcareous gravelly loamy earth with an abundant covering of leaf litter. A sparse mantle of subrounded to rounded, medium to coarse (0.6–6 cm) calcrete concretions is often present. The uppermost soil layer is generally a light, fine sandy loam, which differs in being much sandier than most Calcareous loamy earth soils formed from mafic and ultramafic parent material, which have a surface texture of sandy clay loam or heavier. DEMF also occurs on Alkaline (grey, red or yellow–brown) shallow loamy duplex soils on the footslopes of some hills and rises to the south and south-east of Norseman in the Dundas, Nanambinia and Fraser Range zones.

Dense mixed eucalypt and melaleuca forest consisting of *Eucalyptus fraseri* subsp. *melanobasis, E. laevis and E. urna* with *Melaleuca lanceolata* on a Red shallow loamy duplex in the Yardilla land system

Dundas blackbutt, melaleuca forest with *Eucalyptus dundasii* (Dundas blackbutt) and *Melaleuca sheathiana* (boree) on a Calcareous shallow loam in the Dundas land system

DEMF is similar to the ETTW. The soils have a similar pedogenic origin that is partially derived from calcareous loess (Doepel 1973), and compositional similarities within the tree and tall shrub strata, but the physiognomy of vegetation differs. DEMF, like ETTW, is characterised by a well-developed tall shrub stratum. However, in DEMF, this stratum is often contiguous with dense groves of *Melaleuca*, resulting in a closed canopy which, in conjunction with dense leaf litter, constrains any understorey development. Topographically, they are slightly dissimilar, with DEMF typically occurring on the level to lower slopes of very gently undulating plains, whereas ETTW occurs on upper slopes of undulating plains that are gradational with gently inclined, broad rolling rises.

Physiognomy and composition of vegetation

DEMF occurs as a moderately close to closed (≥25% PFC) eucalypt forest over dense groves of moderately close to closed (>20% PFC) *Melaleuca* species. Tall (<20 m) eucalypts dominate the tree stratum, with species dominance varying depending on location. The mid and low shrub strata are poorly developed. Perennial grasses are rare.

The dominant and common species by strata:

Trees:	Dominant – *Eucalyptus* spp.; occasionally *E. dundasii*, *E. fraseri* subsp. *fraseri*, *E. fraseri* subsp. *melanobasis*, *E. lesouefii*, *E. transcontinentalis*, *E. urna* Common – *Eucalyptus dundasii*, *E. lesouefii* or *E. urna* (when other species are dominant) Other – *Eucalyptus laevis*
Mallees:	Dominant – rarely present as a recognisable stratum; occasionally *Eucalyptus oleosa* subsp. *oleosa*
Tall shrubs:	Dominant – *Melaleuca* spp. Common – *Exocarpos aphyllus*, *Melaleuca lanceolata*, *M. pauperiflora* subsp. *fastigiata*, *M. sheathiana* Others – variable; *Geijera linearifolia*, *Santalum acuminatum*
Mid shrubs:	Dominant – rarely present as a recognisable stratum; occasionally *Eremophila scoparia* Common – *Cratystylis conocephala*, *Eremophila scoparia* Others – *Eremophila interstans* subsp. *interstans*, *E. ionantha*
Low shrubs:	Dominant – rarely present as a recognisable stratum Common – *Halgania andromedifolia*, *Olearia muelleri* Others – variable; *Acacia acoma*, *Olearia calcarea*, *Scaevola spinescens*, *Westringia rigida*

Ecological disturbance

Most plants are not particularly palatable or preferred by livestock. In some instances, DEMF is associated with areas that displayed evidence of historical wood harvesting or fire. In these areas, the physiognomy of the tree and tall shrub strata may be a competitive regrowth response to the disturbance. However, in other areas there was no obvious evidence of disturbance and the physiognomy appeared to be a natural state, particularly for DBMF. Research on *Eucalyptus dundasii* indicates it has significant allelopathic properties (Wu et al. 2011; Zhang et al. 2012) which may be influencing the sparsity of undergrowth in these habitats. Other factors associated with litter coverage, competition for water, tree canopy and/or root system extent could also be manipulating structure and composition.

Gradational associations

DEMF transitions into ETTW, EFBW or Plain eucalypt, eremophila woodland (PEEW, #59) as mixed non-halophytic shrubs, *Cratystylis conocephala* (false bluebush) or eremophilas, respectively, begin to increase through the mid and low shrub strata, and as the upper canopy coverage becomes less dense and/or melaleuca groves less contiguous.

Land systems

DEMF is a major habitat type in the Dundas land system and a minor habitat type in the Charlina, Doney, Halbert, Harms, Noganyer, Sharpe and Yardilla land systems.

Uncommon habitats in the Sheetwash plain woodland habitat group

56 *Eucalyptus oleosa*, saltbush woodland (EOSW)

Sampling

3 inventory sites, 8 traverse points

General information

EOSW is described for the first time. It is similar to Eucalypt, false bluebush woodland (EFBW, #53) in species composition. However, EOSW is considered a distinctive habitat type rather than a subtype of EFBW because of its denser canopy, prominence of *Atriplex* (saltbush) species in the low shrub strata, and its frequent occurrence on low rises and lower footslopes near Fraser Range. Soils are commonly Calcareous gravelly shallow loam or Calcareous shallow loam over rock. A surface mantle of variable coarse (20–60 mm), subrounded, calcrete gravels may be present.

Physiognomy and composition of vegetation

EOSW occurs as a moderately close to closed (≥25% PFC) eucalypt (mallee) woodland dominated by *Eucalyptus oleosa* subsp. *oleosa* (giant mallee), with the low shrub strata dominated by *Atriplex* species. Other eucalypts include *E. dundasii* (Dundas blackbutt), *E. lesouefii* (Goldfields blackbutt), *E. salubris* (gimlet) and *E. urna*. The tall shrub stratum is variably developed, and the mid shrub stratum is typically poorly developed. Perennial grasses are often absent.

The dominant and common species by strata:

Trees:	Dominant – rarely present other than as emergents
	Common – *Eucalyptus salubris*, *E. urna*
	Others – *Eucalyptus dundasii*, *E. fraseri* subsp. *melanobasis*, *E. lesouefii*
Mallees:	Dominant – *Eucalyptus oleosa* subsp. *oleosa*
	Other – *Eucalyptus protensa*
Tall shrubs:	Dominant – rarely present as a recognisable stratum
	Common – *Eremophila interstans* subsp. *interstans* (KI), *E. scoparia* (KI), *Geijera linearifolia*, *Santalum acuminatum*
Mid shrubs:	Dominant – rarely present as a recognisable stratum
	Common – *Eremophila scoparia* (KI)
	Others – *Acacia hemiteles* (KI), *Cratystylis conocephala*, *Eremophila decipiens*, *E. ionantha*, *Pimelea microcephala*

Low shrubs:	Dominant – *Atriplex stipitata* (KI), *A. vesicaria* (KD) Common – *Enchylaena tomentosa* (KD), *Rhagodia crassifolia* (KD), *R. drummondii* (KD) Others – *Olearia calcarea*, *O. muelleri*, *Ptilotus obovatus*, *Scaevola spinescens*
Perennial grasses:	Dominant – not present as a recognisable stratum Other – *Austrostipa elegantissima*
Other plant forms:	Common – *Sclerolaena diacantha* (perennial herb) Other – *Sclerolaena obliquicuspis* (perennial herb)

Priority flora

Eucalyptus fraseri subsp. *melanobasis* (Priority 2) was recorded at one site.

Ecological disturbance

EOSW response to disturbances is similar to other eucalypt woodlands with saltbush-dominated understoreys. The most reliable indicator of vegetation condition for grazing impacts is the density and composition of palatable understorey shrubs. The presence and density of *Atriplex vesicaria* with tussocks of the perennial *Austrostipa elegantissima* (feather speargrass) are reliable indicators of good condition, along with other palatable chenopods such as *Enchylaena tomentosa* (ruby saltbush) and *Sclerolaena diacantha* (grey bindii). In some degraded areas, *A. stipitata* may replace *A. vesicaria*, though it is not definitive evidence of a grazing-induced succession because it can also dominate some ungrazed habitats. In poor condition, unpalatable species, such as *Acacia hemiteles* (tan wattle), *Eremophila interstans* subsp. *interstans* and *E. scoparia* (broom bush), are often abundant.

Historic grazing pressure singularly and/or on regrowth after fire has reduced some EOSW habitats to *Eucalyptus oleosa*, bindii woodland (EOBW, #57). Saltbush is not well adapted to fire and where grazing pressure has inhibited recovery after fire, the saltbush seedbank has been drastically reduced or eliminated. In poor condition EOSW can become so degraded that only *Sclerolaena* species (bindiis) are present.

Examples of *Eucalyptus oleosa*, saltbush woodlands: left) community in good condition with an understorey of mixed *Atriplex* (saltbush) species; right) a degraded community that has been reduced to a eucalypt woodland dominated by *Sclerolaena* (bindii) species

Gradational associations

Near the hills and rises associated with Fraser Range, a mosaic of habitat types exists. Most habitat types have distinct boundaries because of changes in gradient and soil type. Upslope of the footslopes supporting EOSW, this habitat typically abuts Stony dodonaea low shrubland (SDLS, #23). Downslope, EOSW commonly abuts Atriplex low shrubland (ATLS, #76), Speargrass and wallaby grass open grassland (SWOG, #77) or Annual herbland (ANNH, #78) as soil textures become heavier and the tree canopy disappears. Poor condition EOSW can also occur in various forms as it degrades and transitions into EOBW, though this is largely influenced by distance from water and whether grazing is ongoing.

Where footslopes and rises merge with the surrounding undulating, calcareous plains, and soils become deeper and lighter-textured, EOSW often transitions into Eucalypt, false bluebush woodland (EFBW, #53), with *Cratystylis conocephala* (false bluebush) becoming more conspicuous through the understorey.

Land systems

EOSW is a major habitat type in the Yardilla land system and a minor habitat type in the Gnamma, Symons, Wyralinu and Yardina land systems.

57 *Eucalyptus oleosa*, bindii woodland (EOBW)

Sampling

1 inventory site, 21 traverse points

General information

EOBW is described for the first time. It is restricted to the lower footslopes and low rises associated with Fraser Range in the south-east of the survey area. EOBW is considered to be a degraded vegetation state of *Eucalyptus oleosa*, saltbush woodland (EOSW, #56). Possibly caused by historic grazing pressure, in isolation or during recovery after fire, the saltbush seedbank has been eliminated and only *Sclerolaena* species (bindiis) remain to germinate when seasons are favourable. Soils are commonly Calcareous gravelly shallow loam, Calcareous stony soil and Alkaline red shallow loamy duplex.

Physiognomy and composition of vegetation

EOBW consists of moderately close to closed (≥25% PFC) eucalypt (mallee) woodland dominated by *Eucalyptus oleosa* subsp. *oleosa* (giant mallee) over very scattered to scattered perennial and annual herbs. No specific species dominate the tall, mid or low shrub strata and they are poorly developed. Perennial shrubs, infrequently observed as isolated individuals, include *Atriplex stipitata* (kidney saltbush), *Enchylaena tomentosa* (ruby saltbush), *Ptilotus obovatus* (cotton bush) and *Rhagodia* spp. *Sclerolaena diacantha* (grey bindii) and *S. obliquicuspis* (limestone bindii) are the most frequently observed species comprising the herbland. Similar eucalypts observed in EOSW are also present in EOBW, such as *E. dundasii* (Dundas blackbutt), *E. laevis*, *E. lesouefii* (Goldfields blackbutt), *E. salubris* (gimlet) and *E. urna*.

Priority flora

Eucalyptus fraseri subsp. *melanobasis* (Priority 2) was recorded at one site.

Ecological disturbance

EOBW is considered to represent a post-transition, vegetation state when EOSW becomes severely degraded. The density and composition of the understorey, which has largely been reduced to biennial and annual herbs, is seasonally dependent. In dry seasons, these areas are susceptible to wind erosion because the short-lived herbs die and leave the ground exposed.

In improving condition EOBW may contain palatable perennial shrubs and herbs such as *Enchylaena tomentosa*, *Ptilotus obovatus*, *Rhagodia crassifolia* (fleshy saltbush), *R. drummondii* (lake-fringe rhagodia), *Sclerolaena diacantha* and perennial grasses such as *Rytidosperma caespitosum* (wallaby grass) and *Enneapogon* spp. and a stable cryptogamic crust. In areas experiencing ongoing grazing pressure palatable species are scarce and the cryptogamic crust is disturbed or absent.

Gradational associations

EOBW is often downslope of Stony dodonaea low shrubland (SDLS, #23) and upslope of Speargrass and wallaby grass open grassland (SWOG, #77) or Annual herbland (ANNH, #78). EOBW can occur in various stages of transition as EOSW degrades (or recovers) depending on the distance from water and whether grazing is ongoing.

Land system

EOBW is a major habitat type in the Yardilla land system.

I Depositional plain woodland over shrubland habitats

As described in the introduction to Sheetwash plain woodland habitat (Group H), the other common eucalypt associations in the survey are those woodlands in topographically lower landscapes, such as alluvial plains. The boundary between the lower slopes of some sheetwash plains and alluvial plains supporting eucalypt woodlands is often indistinct because of subtle, gradational changes between overstoreys and understoreys. Many of the same agents that have disturbed eucalypt woodlands on sheetwash plains have also affected, and continue to modify, the eucalypt woodlands on lowland landforms.

One habitat type in this group, Plain eucalypt, saltbush woodland (PESW, #58), has been affected more by grazing than perhaps any other eucalypt woodland in the region because of its highly palatable chenopod understorey. In some historically grazed PESW habitats where saltbushes have been extensively reduced or eliminated, these habitats have been invaded by unpalatable species, such as *Eremophila scoparia* (broom bush), to such extent that they now resemble Plain eucalypt, eremophila woodland (PEEW, #59). These changes are described in each habitat type.

Woodland habitat types on alluvial plains draining or adjacent to salt lakes and playas make up most of this group. Other woodland habitat types are commonly associated with lunettes and sand sheets derived from adjacent salt lakes and playas. Unlike the woodlands with chenopod understoreys, lakeside woodland habitat types typically consist of unpalatable understoreys and are usually unaffected by grazing.

58 Plain eucalypt, saltbush woodland (PESW)

Sampling

32 inventory sites, 451 traverse points

General information

PESW was previously recognised as a subtype of Plain eucalypt, chenopod woodland (PECW) in the north-eastern Goldfields (Pringle et al. 1994) and Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b) surveys. It was split according to the dominant genus of the understorey: PESW for saltbushes (*Atriplex*) and PEBW for bluebushes (*Maireana*). However, PESW was described as a distinct habitat in the Kambalda survey (Payne et al. 1998a) because of its prominence throughout the central and eastern parts of that area. It is also described as a distinct habitat type in the southern Goldfields.

PESW is found throughout this survey area in a variety of situations. PESW is predominantly associated with level to very gently undulating plains, which commonly lack a surface mantle, except for occasional surfaces which have an abundant, fine (2–6 mm), subrounded ironstone gravel lag. PESW also occurs adjacent to salt lake systems, particularly through the central and southern parts of the survey. To a lesser extent, PESW can also be associated with upland landforms where it abuts stony rises or the footslopes of hills. In such circumstances, PESW may have a mantle with attributes determined by the exposed bedrock or upslope scree.

Soils vary according to the topographic locality, reflected in the variety of eucalypt species above the saltbush understorey. Typically, Calcareous loamy earth or Red loamy earth soils are associated with lower sheetwash plains grading downslope first to clay loam, then to Red–brown non-cracking clay and finally to cracking clay soils in sumps on alluvial plains. The footslope soils are variable Alkaline loamy duplex soils, with the texture influenced by the presence of seeplines and drainage foci. Alluvial fans and sluggish drainage tracts associated with greenstones often contain Self-mulching cracking clay soils.

Physiognomy and composition of vegetation

PESW typically occurs as a scattered to moderately close (>10–30% PFC) eucalypt woodland with a well-developed low shrubland dominated by *Atriplex* species. The variety of eucalypts is influenced by geology, topography or regional distribution. The tree stratum is frequently dominated by *Eucalyptus salmonophloia* (salmon gum) to 25 m tall, or co-dominated with *E. salubris* (gimlet) to 6 m, with PFC of the tree overstorey ranging from 2.5% to 25%, though PFC can exceed 50% in narrow drainage tracts. *E. celastroides* subsp. *celastroides* (mirret) and *E. lesouefii* (Goldfields blackbutt) are often present. While the understorey remains similar in the west and south-west of the survey area, adjacent to lake country (Doney, Garratt and Hopeside land systems), the tree overstorey commonly includes, or is replaced by, *E. longicornis* (red morrel), *E. melanoxylon* (black morrel) and/or *E. urna*. The low shrubland is most frequently dominated by *Atriplex vesicaria* (bladder saltbush), though *A. bunburyana* (silver saltbush) and/or *A. stipitata* (kidney saltbush) may also dominate or be co-dominant. Scattered *A. nummularia* subsp. *spathulata* (old man saltbush) is common in the mid shrub stratum. Sometimes the low shrub stratum is denser than the tree overstorey (15% to >50% PFC), particularly when associated with sluggish drainage tracts. The tall shrub stratum is variable and perennial grasses are patchily distributed, though composition and abundance of these 2 strata can be significantly affected by grazing and seasonal conditions.

The dominant and common species by strata:

Trees:	Dominant – *Eucalyptus salmonophloia*, *E. salubris*; occasionally *E. longicornis* (in the west), *E. melanoxylon* (west), *E. urna* (in the south-west) Common – *Eucalyptus lesouefii* Other – *Pittosporum angustifolium*
Mallees:	Dominant – rarely present as a recognisable stratum Common – *Eucalyptus celastroides*, *E. celastroides* subsp. *celastroides* Others – *Eucalyptus griffithsii* (often associated with greenstones), *E. oleosa* (around footslopes of Fraser Range)
Tall shrubs:	Dominant – various *Eremophila* spp. Common – *Eremophila interstans* subsp. *interstans* (KI), *E. scoparia* (KI), *Exocarpos aphyllus*, *Santalum acuminatum* Others – *Acacia acuminata*, *A. burkittii*, *A. hemiteles* (KI), *Dodonaea viscosa* subsp. *angustissima*
Mid shrubs:	Dominant – *Atriplex nummularia* subsp. *spathulata*; occasionally *Eremophila* spp. Common – *Eremophila decipiens* (KI), *E. scoparia* (KI), *Maireana pyramidata*, *M. sedifolia*, *Senna artemisioides* subsp. *filifolia* (KI) Others – *Eremophila glabra* (KD), *E. ionantha*
Low shrubs:	Dominant – *Atriplex vesicaria* (KD); occasionally *Atriplex bunburyana* (KD), *A. stipitata* (KI) Common – *Enchylaena tomentosa* (KD), *Lycium australe*, *Maireana georgei* (KD), *M. pyramidata*, *M. radiata*, *M. tomentosa*, *M. triptera*, *Olearia muelleri*, *Ptilotus obovatus*, *Rhagodia drummondii* (KD), *Scaevola spinescens*
Perennial grasses:	Dominant – rarely present as a recognisable stratum Common – *Austrostipa elegantissima* (KD), *A. scabra* Other – *Rytidosperma caespitosum*
Other plant forms:	Common – *Ptilotus exaltatus* (annual herb), *Sclerolaena diacantha* (perennial herb), *S. drummondii* (perennial herb), *S. obliquicuspis* (perennial herb) Others – *Atriplex acutibractea* (perennial herb; KI), *A. codonocarpa* (perennial herb; KI), *Sclerolaena cuneata* (perennial herb; KI), *S. patenticuspis* (perennial herb; KI), *Roepera* spp.

Priority flora

Grevillea phillipsiana (Priority 1) was recorded at one site.

Ecological disturbance

Like other eucalypt woodlands with chenopod-dominated understoreys, the density and composition of palatable understorey shrubs provides the most reliable indicator of condition and grazing impacts. For PESW in good condition, reliable indicators are the presence and density of *Atriplex bunburyana* and/or *A. vesicaria*, with tussocks of the perennial *Austrostipa elegantissima* (feather speargrass), as well as a mixture of other palatable chenopods, such as *Enchylaena tomentosa* (ruby saltbush), *Maireana georgei* (George's bluebush), *M. tomentosa* (felty bluebush) and *Sclerolaena diacantha* (grey bindii). In poor condition, unpalatable shrubs –

such as *Acacia hemiteles* (tan wattle), *Eremophila interstans* subsp. *interstans*, *E. scoparia* (broom bush) and *Senna artemisioides* subsp. *filifolia* (desert cassia) – are often abundant or even dominate. In areas that are in poor condition and degraded, unpalatable biennial herbs – such as *Atriplex acutibractea* (toothed saltbush), *A. codonocarpa* (flat-topped saltbush), *Sclerolaena cuneata* (yellow bindii), *S. obliquicuspis* (limestone bindii) and *S. patenticuspis* (spear-fruit copper burr) – may also be present in large numbers during favourable seasons. In some degraded areas, *A. stipitata* – which looks similar to *A. vesicaria*, but its bitter taste is not preferred by livestock – may replace more palatable saltbushes. However, its dominance is not definitive evidence of a grazing-induced succession because it is also common in some ungrazed habitats.

Some PESW habitats have become so significantly invaded by *Eremophila scoparia* they now resemble Plain eucalypt, eremophila woodland (PEEW, #59). This resemblance may be a transitional vegetation state, caused by historic grazing pressure or regrowth after fire, while under the influence of excessive herbivory from livestock, goats, kangaroos or rabbits. In some instances, the transition from PESW to PEEW appears to be permanent because of the near-total elimination of the saltbush seed source while unpalatable shrubs have proliferated. An indication that the understorey of a post-transition PESW – now resembling PEEW – was once dominated by chenopods is the abundance of annual or biennial *Atriplex* (saltbushes) and *Sclerolaena* (bindiis) species. These short-lived chenopods occur throughout the survey and are especially common in alkaline soils where they may be prolific during favourable seasons. Elsewhere, they typically have low frequency. They are also among the first re-colonisers of disturbed chenopod shrublands. Naturally occurring PEEW may contain occasional *Sclerolaena* species, but degraded PESW may contain large numbers of unpalatable short-lived Chenopodiaceae herbs.

Examples of a Plain eucalypt, saltbush woodland: left) a community in good condition; right) a community in poor condition after it has become encroached by *Eremophila scoparia* (broom bush)

There are species that have low or no fire tolerance within PESW communities. In the tree stratum, *E. salubris* is particularly susceptible, with fires that completely scorch a canopy being capable of causing tree deaths (Gosper et al. 2013a). The chenopod-dominated understorey is also poorly adapted to fire. The degree of damage a fire can cause depends on fire temperature. A cool, mild fire may not kill *Maireana sedifolia,* but *A. vesicaria* does not withstand any burning (Fitzgerald 1976; Graetz and Wilson 1984). Chenopod regeneration after fire depends on seed germination; if grazing pressure prevents recovery after fire there is a risk of completely exhausting the seed bank (Hodgkinson and Griffin 1982). The extent of PEEW throughout land systems and habitats considered former PESW could be the legacy of the 1974–75 and 1975–76 fires in the Kalgoorlie–Nullarbor districts (Fitzgerald 1976; Lay 1976;

Burnside 1985) in combination with the effect of all herbivorous grazing on the regrowth in the years after fire.

Despite high fire sensitivity, PESW can have fire-return intervals of hundreds of years (O'Donnell et al. 2011a). These extremely long periods are partially influenced by proximity of some communities to salt lakes, which act as natural fire barriers. The other factor influencing long fire-return intervals, and reducing the likelihood of fire spreading, is that mature PESW habitats have high, open structured tree canopies and discontinuous leaf litter on the woodland floor. Floristic analysis of diversity and composition indicates these fire-sensitive woodlands require intervals between fires of more than 200 years to reach maturity (Gosper et al. 2013b).

As well as grazing and fire impacts, the saltbush-dominated understorey of PESW is also susceptible to moisture stress. Species of *Atriplex* respond to stress by shedding leaves but can quickly recover in response to significant rainfall events. During this recovery phase saltbush needs protection from grazing to allow mature plants to recover vigour and set seed, and for establishment of germinated plants.

Another change in some habitats among greenstone-dominated landscapes has come about through wood harvesting, which has left some PESW resembling Bladder saltbush low shrubland (BLSS, #72). Some former woodlands with a low saltbush understorey have been so heavily logged they are now shrublands, with the trees unable to regenerate to earlier densities. While the BLSS on lake margins is considered a natural feature, in some instances BLSS within woodland settings are former PESW that have been clear-felled of timber.

Gradational associations

Slightly upslope of the alluvial plains, where lighter-textured and better drained soils associated with undulating, calcareous low rises occur, PESW often transitions into Plain eucalypt, bluebush woodland (PEBW, #52), with bluebush becoming more common through the understorey. Where plains merge with the footslopes of uplands and soils become shallower and stonier, PESW transitions into Greenstone eucalypt, saltbush woodland (GESW, #28), with *Eucalyptus salmonophloia* replaced by *E. lesouefii* or, less often, *E. griffithsii* (Griffith's grey gum).

Predominantly west of the greenstone-dominated landscapes, PESW transitions out of broad alluvial drainage tracts into adjacent slightly higher and sandier-textured plains supporting Plain eucalypt, eremophila woodland (PEEW). Here, *E. salmonophloia* is co-dominant with or replaced by *E. transcontinentalis* (redwood), and saltbushes are replaced by *Eremophila scoparia.* Some PESW habitats have also been degraded to PEEW.

PESW transitions into Plain eucalypt, halophytic woodland (PEHW, #60) in areas where soil salinity increases and halophytes become more prominent through the understorey. Adjacent to lake country, PESW commonly transitions downslope into Plain mixed halophyte shrubland (PXHS, #70) or Bladder saltbush low shrubland (BLSS, #72).

Land systems

PESW is the dominant habitat type in the Garratt, Gumland and Hopeside land systems, a major habitat type in the Coolgardie and Woolibar land systems and a minor habitat type in the Doney, Illaara, Kanowna, Lefroy, Moriarty and Yardilla land systems. It features in many land systems in narrow valley floors and sluggish drainage tracts, particularly where they are adjacent to or associated with mafic and greenstone landforms, and at ecotone boundaries on alluvial fans.

59 Plain eucalypt, eremophila woodland (PEEW)

Sampling

21 inventory sites, 314 traverse points

General information

PEEW was first described in the Kambalda survey (Payne et al. 1998a). While it occurs throughout the southern Goldfields, it is most common in the west in association with the Youanmi South Zone. PEEW is common to the broad, level valley floors forming drainage tracts between the extensive sandplains, as well as very gently inclined to level sheetwash plains adjacent to salt lakes. It is also encountered in wide drainage tracts that collect run-off from large granite outcrops and associated landforms. The level to very gently inclined plains of PEEW commonly lack a surface mantle, except when it abuts upland landforms where a variable mantle may be present. Soils typically consist of Alkaline red shallow loamy duplex, Red loamy earth, Calcareous loamy earth and Calcareous gravelly shallow loam. Within some broad paleodrainage tracts, calcrete platforms may occur, often with a variable mantle of subrounded to rounded, medium to coarse (0.6–6 cm) calcrete concretions over Calcareous shallow loam.

PEEW is also common in the greenstone-dominated Kambalda Zone. Here, the 2 most common understorey types of woodlands on alluvial plains, which occur independently of the eucalypt overstorey, are PEEW and the saltbush-dominated understorey of Plain eucalypt, saltbush woodland (PESW, #58). Aside from minor topographic differences, subtle edaphic variations are likely responsible for the differences between the associations. Beard (1975) suggested soil alkalinity as a possible factor influencing species distribution, with the less alkaline soils on higher ground occupied by *Eremophila* species, and the more alkaline, lower lying areas supporting chenopod species. However, within the Kambalda Zone there are 2 forms of PEEW: the 'natural' state as identified in the Youanmi South Zone (see Harvey 2014); and a degraded state of PESW which is affected by scrub encroachment of *Eremophila scoparia* (broom bush) (see PESW Ecological disturbance section for more detail). The degraded PESW, which now resembles PEEW, tends to occur on slightly heavier-textured soils ranging from Calcareous loamy earth to clay loam or clay soils.

Physiognomy and composition of vegetation

PEEW typically occurs as a moderately close (>20–30% PFC) eucalypt woodland that is characterised by a well-developed mid and low shrubland dominated by *Eremophila* species and generally devoid of halophytic species. While a few halophytes may be present, this habitat does not support a complex of Chenopodiaceae. Perennial grasses are infrequent.

The dominant overstorey consists of various eucalypts over 15 m tall, with 5–30% PFC. Typically, *Eucalyptus salmonophloia* (salmon gum) or *E. transcontinentalis* (redwood) dominate these woodlands, though other eucalypts are frequently present such as *E. celastroides* (mirret), *E. lesouefii* (Goldfields blackbutt), *E. salubris* (gimlet) or *E. yilgarnensis* (yorrell). The variability in dominant eucalypt species is influenced by regional distribution, geology and topography. The mid shrub layer supports a variety of *Eremophila* species, with PFC ranging from 2.5% to 15%.

Occurring independently of the eucalypt overstorey are 2 broad associations which are differentiated by the dominant species of *Eremophila* present, with *E. ionantha* (violet-flowered eremophila) in the west in the Youanmi South Zone, and *E. scoparia* in central and eastern parts in the Kambalda Zone. In both associations, the low shrub stratum supports a variety of non-halophytic species, the most common being *Eremophila* spp., *Olearia muelleri* (Goldfields daisy) and *Scaevola spinescens* (currant bush), with PFC ranging from 2.5% to 15%.

The dominant and common species by strata:

Trees:	Dominant – *Eucalyptus salmonophloia*, *E. transcontinentalis*; occasionally *E. lesouefii*, *E. salubris*, *E. yilgarnensis*
	Common – *Eucalyptus lesouefii* (when other species are dominant)
	Other – *Melaleuca pauperiflora* subsp. *fastigiata*
Mallees:	Dominant – rarely present as a recognisable stratum
	Common – *Eucalyptus celastroides*, *E. gracilis*, *E. oleosa* subsp. *oleosa*
Tall shrubs:	Dominant – variable; occasionally *Eremophila oppositifolia*, *E. scoparia* (KI), *Exocarpos aphyllus*, *Melaleuca pauperiflora* subsp. *fastigiata*
	Common – *Acacia colletioides*, *A. hemiteles* (KI), *A. nyssophylla*, *Alyxia buxifolia*, *Eremophila scoparia* (KI), *Santalum acuminatum*
	Other – *Santalum spicatum*
Mid shrubs:	Dominant – *Eremophila ionantha*, *E. scoparia* (KI); occasionally *Acacia hemiteles* (KI), *Senna artemisioides* subsp. *filifolia* (KI)
	Common – *Eremophila caperata*, *E. decipiens* (KI)
	Others – *Cratystylis conocephala*, *Eremophila glabra* (KD), *Maireana sedifolia*
Low shrubs:	Dominant – *Olearia muelleri*, *Scaevola spinescens*
	Common – *Grevillea acuaria*, *Maireana pentatropis*, *Olearia pimeleoides*, *Ptilotus obovatus*, *Rhagodia drummondii* (KD)
	Others – *Acacia erinacea*, *Atriplex stipitata* (KI), *A. vesicaria* (KD), *Enchylaena tomentosa* (KD), *Maireana georgei* (KD), *M. triptera*, *Westringia rigida*
Perennial grasses:	Dominant – rarely present as a recognisable stratum
	Common – *Austrostipa elegantissima* (KD), *A. scabra*
	Others – *Austrostipa platychaeta* (KD), *Triodia scariosa*
Other plant forms:	Common – *Sclerolaena diacantha* (perennial herb)
	Others – *Ptilotus exaltatus* (annual herb), *Roepera* spp.

Priority flora

Grevillea phillipsiana (Priority 1) was recorded at one site.

A Plain eucalypt, eremophila woodland dominated by *Eucalyptus yilgarnensis* (yorrell) on a Red loamy earth soil

Ecological disturbance

Where PEEW communities occur naturally, particularly in the west of the survey area, grazing has little impact because there are few palatable species present.

In the greenstone-dominated Kambalda Zone, some degraded PESW habitats now resemble PEEW because of the proliferation of the unpalatable *Eremophila scoparia*. It is likely that disturbance events are responsible for the differences in species composition, which could be a legacy from historic grazing, woodcutting, hailstorms and fires. These factors, singularly or in conjunction, could have altered the species composition in a manner that is difficult to understand so many years after the event. Regardless, the near-total elimination of the saltbush seed source, while *Eremophila* species have increased, has caused the transition of PESW to resemble PEEW and is likely to be a permanent post-transition vegetation state.

Not all *E. scoparia*-dominated PEEW are considered to be degraded PESW and there are locations where the association is naturally occurring. However, where there is no clear distinction in soil type, it can be difficult to differentiate between PEEW and scrub-encroached, degraded PESW habitats. One indication that a PEEW with an *E. scoparia*-dominated understorey may be degraded PESW is the density of biennial or short-lived perennial *Atriplex* (saltbushes) and *Sclerolaena* (bindiis) species. While *Sclerolaena* species occur infrequently in natural PEEW, in degraded PESW that resembles PEEW, there may be an abundance in these and other unpalatable herbs during favourable seasons – species such as *Atriplex acutibractea* (toothed saltbush), *A. codonocarpa* (flat-topped saltbush), *Sclerolaena cuneata* (yellow bindii), *S. obliquicuspis* (limestone bindii) and *S. patenticuspis* (spear-fruit copper burr)). These species are among the first re-colonisers of alkaline landscapes and their presence may indicate a former, now degraded, chenopod shrubland.

Gradational associations

Where plains supporting PEEW merge with the footslopes of granitic uplands or pavements, there is often a transition into Granitic pediment eucalypt, tall shrub thicket (GETT, #12). Where PEEW abuts rocky outcrop, the ecotone is usually clearly defined because the shallow soils have different geologic origins.

Where level plains supporting PEEW change in gradient this habitat type transitions into either gently inclined sheetwash plains supporting Colluvial slope eucalypt woodland over non-halophytic shrubland (CEWS, #51) in the west, or gently undulating plains supporting Eucalypt, false bluebush woodland (EFBW, #53) in the south-east of the survey. The dominant association of *Eucalyptus salmonophloia* and/or *E. transcontinentalis* over *Eremophila* species in PEEW is gradually replaced by *E. oleosa* subsp. *oleosa* (giant mallee) and *E. urna* co-dominated woodlands, with a variably mixed understorey in CEWS or one dominated by *Cratystylis conocephala* (false bluebush) in EFBW.

In the east of the survey, PEEW often occurs as a component of a broader eucalypt woodland mosaic and intermixes with EFBW and Mallee, hummock grass (spinifex) woodland (MHGW, #35) across subtle ecotone boundaries.

In the greenstone-dominated landscapes of the Kambalda Zone, PEEW transitions from slightly topographically higher, lighter-textured plains into lower lying alluvial drainage tracts supporting PESW. Here, *E. transcontinentalis* and *Eremophila scoparia* are replaced by *E. salmonophloia*, *E. salubris* and saltbushes as soils become more alkaline and heavier textured. However, in some instances these same PESW habitats have been altered through disturbance, are scrub-encroached by *E. scoparia*, and now resemble PEEW.

In areas adjacent to salt lakes, PEEW communities may be quite different from vegetation on bordering landforms because of edaphic factors. Typically, on western lake boundaries there are distinctive differences between habitat types due to increasing salinity and alkalinity, which result in clearly defined ecotone boundaries between habitat types such as Plain mixed halophyte shrubland (PXHS, #70) and Bladder saltbush low shrubland (BLSS, #72). However, on the southern and eastern sides of lake systems, gradations may be subtle where PEEW transitions into Lakeside (sand sheet) eucalypt woodland with shrubs (LSES, #64) or spinifex (LSMX, #63) as the back slopes of windblown lacustrine deposits from lunettes and sand sheets merge into adjacent plains.

Land systems

PEEW is the dominant habitat type in the Doney land system, a major habitat type in the Erayinia and Johnston land systems and a minor habitat type in the Bannar, Cundlegum, Gumland and Lefroy land systems. Infrequent occurrences occur in many land systems in broad drainage tracts adjacent to salt lakes.

60 Plain eucalypt, halophytic woodland (PEHW)

Sampling

9 inventory sites, 114 traverse points

General information

PEHW is described for the first time. It is frequently associated with very gently inclined to level saline stony plains which grade down from the lower footslopes of bordering upland systems. Plains supporting PEHW are regularly overlain by a dense mantle of quartz lag consisting of medium to coarse (0.6–6 cm), angular to subangular rock fragments. Underlying weathered volcaniclastic pavements are infrequently exposed. Soils are typically derived from extensively weathered metasedimentary rocks, often of volcaniclastic origin. They are commonly Saline soils and Calcareous loamy earth or Red loamy earth soils with saline and gypsiferous subsoils. PEHW is also associated with saline alluvial plains marginal to salt lake systems and sluggish drainage tracts on Red–brown non-cracking clay soils with saline and gypsiferous subsoils.

Physiognomy and composition of vegetation

PEHW typically occurs as a scattered to moderately close (>10–30% PFC) eucalypt woodland characterised by a well-developed low shrubland dominated by *Tecticornia* species (samphire). The tree stratum commonly consists of scattered (>10–20% PFC) *Eucalyptus salmonophloia* (salmon gum) or *E. salubris* (gimlet) trees, to 25 m and 15 m tall, respectively. Occasional moderately close (>20–30% PFC) stands of *E. salubris* less than 6 m tall, or less often *E. celastroides* subsp. *celastroides* (mirret), may occur among the taller, mature trees. *E. lesouefii* (Goldfields blackbutt) is also often present. The low shrubland is dominated by *Tecticornia* species, though *Atriplex vesicaria* (bladder saltbush) or *A. bunburyana* (silver saltbush) may sometimes be co-dominant, particularly in habitats in good condition. The low shrub stratum is typically denser than the tree overstorey, particularly when associated with saline alluvial plains and sluggish drainage tracts. The tall and mid shrub strata, when present, are typically poorly developed, occurring as isolated individuals. Perennial grasses are rare.

The dominant and common species by strata:

Trees:	Dominant – *Eucalyptus salmonophloia*, *E. salubris*; occasionally *E. lesouefii* Common – *Eucalyptus lesouefii* (when other species are dominant) Others – *Casuarina pauper*, *Eucalyptus ravida*, *E. transcontinentalis*
Mallees:	Dominant – rarely present as a recognisable stratum Others – *Eucalyptus celastroides*, *E. celastroides* subsp. *celastroides*
Tall shrubs:	Dominant – rarely present as a recognisable stratum Common – *Eremophila interstans* subsp. *interstans* (KI), *E. scoparia* (KI), *Exocarpos aphyllus*, *Santalum acuminatum*
Mid shrubs:	Dominant – rarely present as a recognisable stratum Common – *Atriplex nummularia* subsp. *spathulata*, *Eremophila glabra* (KD), *E. scoparia* (KI), *M. sedifolia* Other – *Maireana pyramidata*
Low shrubs:	Dominant – *Tecticornia disarticulata*, *T. doliiformis*; occasionally *Atriplex vesicaria* (KD), *Tecticornia halocnemoides* Common – *Atriplex bunburyana* (KD), *A. stipitata*, *A. vesicaria* (KD), *Enchylaena tomentosa* (KD), *Maireana tomentosa*, *Olearia muelleri*, *Ptilotus obovatus*, *Rhagodia drummondii* (KD), *Scaevola spinescens* Others – *Lycium australe*, *Maireana georgei* (KD), *Solanum lasiophyllum*, *S. orbiculatum*
Perennial grasses:	Dominant – not present as a recognisable stratum Others – *Austrostipa elegantissima*, *A. scabra*, *Rytidosperma caespitosum*
Other plant forms:	Dominant – not present as a recognisable stratum Common – *Sclerolaena diacantha* (perennial herb), *S. drummondii* (perennial herb) Others – *Carpobrotus* spp. (succulent perennial herb), *Maireana eriosphaera* (perennial herb)

Ecological disturbance

Water quality significantly influences grazing behaviour and utilisation in these habitats, because of the prominence of halophytic shrubs in the understorey. Where good quality water is available, grazing pressure can lead to reductions in palatable halophytic plants. The prominence of key palatable species provides the most sensitive indicator of grazing impact. Under heavy grazing pressure, palatable shrubs – such as *Atriplex bunburyana* (silver saltbush), *A. vesicaria* (bladder saltbush), *Enchylaena tomentosa* (ruby saltbush), *Maireana georgei* (George's bluebush), *Rhagodia drummondii* (lake-fringe rhagodia) and *Sclerolaena diacantha* (grey bindii) – decrease and are eventually eliminated when seed banks are exhausted. With the loss of palatable plants, *Tecticornia* species can come to dominate.

The saline nature of the subsoil makes PEHW susceptible to scald development. The extent of cryptogamic crusting of the soil surface is significantly lower in areas with heavy grazing history and increases susceptibility to erosion. As scalds coalesce, the ability to support plant growth is reduced. The combination of accelerated erosion and the domination by samphire can significantly reduce the pastoral value of this habitat.

The open structured tree canopies, abundance of samphire and absence of continuous leaf litter on the woodland floor of PEHW communities are likely to significantly reduce the spread of fire and favour long periods without fire. The proximity of PEHW to salt lakes, which act as natural fire barriers, could result in fire-return intervals of hundreds of years (O'Donnell et al. 2011a). The similarities in physiognomy and composition of PEHW to Plain eucalypt, saltbush woodland (PESW, #58) habitats would suggest these woodlands also require intervals between fires of more than 200 years to reach maturity (Gosper et al. 2013b).

Gradational associations

PEHW usually has clearly defined boundaries along lower footslopes marginal to upland systems. With changes in underlying geology affecting edaphic factors, PEHW may transition upslope from saline, stony plains and lower footslopes into Greenstone eucalypt, bluebush woodland (GEBW, #27) or Greenstone eucalypt, saltbush woodland (GESW, #28) as *Maireana sedifolia* (pearl bluebush) or *Atriplex vesicaria*, respectively, replace *Tecticornia* species.

PEHW usually has clearly defined boundaries where it is associated with saline alluvial plains and sluggish drainage tracts within various woodland communities because of the differing soil characteristics of adjacent habitat types. However, in Plain eucalypt, bluebush woodland (PEBW, #52) and PESW habitats close to these heavier-textured saline soils, there may be some gradation as samphire becomes less conspicuous, and bluebushes and saltbushes increase through the understorey. PEHW commonly transitions into Plain mixed halophyte shrubland (PXHS, #70) where the tree stratum disappears from the saline alluvial plains, or woodland saline drainage tracts exit into adjacent lake country.

Land systems

PEHW is a major habitat type in the Kanowna land system and a minor habitat type in the Dundas, Gumland, Monger and Woolibar land systems. PEHW also features occasionally in other land systems in narrow valley floors, sluggish drainage tracts and at ecotone boundaries adjacent to salt lake systems.

Examples of Plain eucalypt, halophytic woodland on a saline alluvial plain: left) community in very good condition with abundant *Atriplex vesicaria* (bladder saltbush) and cryptogamic crusting; right) community in poor condition with loss of palatable species, *Tecticornia* spp. being solely dominant and an unstable soil surface with reduced cryptogamic crusting

61 Drainage tract eucalypt woodland (DREW)

Sampling

10 inventory sites, 86 traverse points

General information

DREW is described for the first time. It is associated with drainage tracts carrying flow through broad sheetwash and alluvial plains. It also occurs in upland landscapes where narrow (<500 m) alluvial tracts between undulating plains experience concentrated flows. DREW is most common through the centre of the survey in the greenstone-dominated Kambalda Zone, and less frequently present in the Southern Cross and Dundas zones.

Soils are generally heavier textured than adjacent plains and consist of Red loamy earth, Red shallow loamy duplex and Red–brown non-cracking clay soils, as well as recent alluvial deposits that have not undergone soil differentiation. DREW commonly lacks a surface mantle, except for occasional flow deposits consisting of subrounded to rounded, fine (2–6 mm), ironstone gravel. Occasionally, Self-mulching cracking clay soils may be present where DREW is associated with restricted, sluggish drainage tracts, drainage foci and closed depressions.

Physiognomy and composition of vegetation

DREW occurs as a moderately close to closed (≥20% PFC) eucalypt woodland. The tree stratum is frequently dominated or co-dominated by *Eucalyptus salmonophloia* (salmon gum) up to 25 m tall, and/or *E. salubris* (gimlet) up to 15 m tall. Various other eucalypt species may be present or dominant depending on geology and topography. The tall shrub stratum is typically well developed and moderately close to close (25–50% PFC), and contains thickets frequently dominated by species of *Acacia* or *Eremophila.* Development of the understorey is inversely related to upper canopy coverage. Within a mature DREW community, the understorey is often poorly developed. Perennial grasses are patchily distributed.

The higher density of canopy coverage and greater individual abundance in the tree and tall shrub strata, compared with adjacent habitat types through which the drainage tracts supporting DREW flow, is due to greater run-on and the formation of microhabitats that provide conducive growing conditions. The provision of shelter, improved water availability and accumulation of organic matter assists germination and enhances survival. The composition of understoreys is variable and influenced by the facilitated transportation of seeds into these favourable habitats. A significant proportion of the species within this habitat are berry-bearing, bird-dispersed plants – such as *Enchylaena tomentosa* (ruby saltbush), *Eremophila* species, *Pimelea microcephala* (shrubby riceflower), *Pittosporum angustifolium* (native willow), *Rhagodia drummondii* (lake-fringe rhagodia) and *Scaevola spinescens* (currant bush) – while other plants with large seeds, such as *Santalum acuminatum* (quandong) and *S. spicatum* (sandalwood), have washed in and settled among leaf litter debris.

A drainage tract dominated by *Eucalyptus salmonophloia* (salmon gum) and *E. salubris* (gimlet) over mixed shrubs on a Red shallow loamy duplex soil

The dominant and common species by strata:

Trees:	Dominant – *Eucalyptus salmonophloia*, *E. salubris* Common – *Casuarina pauper*, *Pittosporum angustifolium*
Mallees:	Dominant – occasionally *Eucalyptus griffithsii* Others – *Eucalyptus celastroides*, *E. celastroides* subsp. *celastroides*, *E. yilgarnensis*
Tall shrubs:	Dominant – variable; often *Acacia* spp., *Eremophila* spp. Common – *Acacia acuminata*, *A. burkittii*, *A. hemiteles* (KI), *A. tetragonophylla*, *Eremophila alternifolia*, *E. scoparia* (KI), *Exocarpos aphyllus* Others – *Pimelea microcephala*, *Santalum acuminatum*, *S. spicatum*
Mid shrubs:	Dominant – variable; often *Senna artemisioides* subsp. *filifolia* (KI) Common – *Acacia hemiteles* (KI), *Atriplex nummularia* subsp. *spathulata*, *Eremophila decipiens* (KI), *E. ionantha*, *E. scoparia* (KI), *Senna artemisioides* subsp. *filifolia* (KI)
Low shrubs:	Dominant – variable Common – *Enchylaena tomentosa* (KD), *Grevillea acuaria*, *Olearia muelleri*, *Ptilotus obovatus*, *Rhagodia drummondii* (KD), *Scaevola spinescens* Others – *Maireana triptera*, *Olearia pimeleoides*
Perennial grasses:	Dominant – rarely present as a recognisable stratum Common – *Austrostipa elegantissima* (KD)
Other plant forms:	Common – *Leichhardtia australis* (climber)

Ecological disturbance

Grazing impact is variable and often correlated to distance from water sources. The proliferation of unpalatable shrubs – such as *Acacia hemiteles* (tan wattle), *A. tetragonophylla* (curara), *Eremophila decipiens* (slender fuchsia), *E. scoparia* (broom bush) and *Senna artemisioides* subsp. *filifolia* (desert cassia) – with the demise of palatable species is likely to indicate a grazing-induced change.

Gradational associations

DREW frequently has species common to the adjacent communities through which the drainage tracts flow. Habitat margins tend to be gradational and are more apparent through structural changes in the density of the strata rather than changes in species composition. With the northern transition from the South-western Interzone (Beard 1990) and Coolgardie bioregion (Environment Australia 2000) to the Eremaean Botanical Province and Murchison bioregion, eucalypts become less common in the overstorey, and DREW is replaced by Drainage tract acacia shrubland (DRAS, #49) or Drainage tract acacia shrubland or woodland with chenopod understorey (DACS, #50).

Land systems

DREW is common through the centre of the survey and features in many land systems, particularly where drainage tracts flow through alluvial plains associated with mafic and greenstone-dominated landforms. It is particularly common in the Coolgardie, Doney, Gumland, Illaara, Johnston, Kanowna, Moriarty and Woolibar land systems.

62 Playa plain woodland (PPWL)

Sampling

7 inventory sites

General information

PPWL is described for the first time. It is a woodland community associated with playa plains. Playa plains are broad valley floors that were formerly ancient rivers. These level plains typically lack stream channels and only intermittently hold water in infrequent, occluded closed depressions or playas which are prone to evaporation. Soils are predominantly Alkaline yellow–brown shallow sandy duplex and are often highly sodic, and sometimes gypsiferous at depth. Where PPWL extends up onto adjacent lunettes and dunes, soils may change to Pale deep sand or Yellow deep sand. At several sites, the soils were affected by acidic and saline groundwater, and a highly acidic horizon in subsoil that was originally alkaline has formed.

Physiognomy and composition of vegetation

PPWL habitats typically occur as moderately close to closed (≥20% PFC), low (<10 m) woodland, which is characterised by moderately close to close (>20–50% PFC) groves of melaleucas or stands of eucalypts. While playa plains are geomorphically similar, the species of *Eucalyptus* and *Melaleuca* within them may vary according to regional distribution. Infrequent, tall (<25 m) *Eucalyptus salicola* (salt gum) may occur among the tree stratum, standing above the contiguous low woodland composed of mallees or melaleucas. The mid and low shrub strata are variably developed and typically consist of non-halophytic shrubs. If the tree and/or tall shrub strata contains dense, contiguous melaleuca groves or eucalypt stands, the mid and low shrub strata may be absent. Perennial grasses are sparse to absent. Perennial herbs, sedges and rushes such as *Dianella revoluta* (blueberry lily), *Lepidosperma drummondii* and *Lomandra effusa* (scented matrush) are common.

The dominant and common species by strata:

Trees:	Dominant – rarely present as a recognisable stratum; occasionally *Eucalyptus salicola, E. transcontinentalis* Common – *E. salicola* (when mallee species are dominant) Others – *Eucalyptus longicornis*, *E. salmonophloia*
Mallees:	Dominant – variable; often *Eucalyptus eremophila*; occasionally *E. alipes*, *E. diptera*, *E. gracilis*, *E. horistes*, *E. scyphocalyx** Others – *Eucalyptus leptophylla**, *E. oleosa* subsp. *oleosa*
Tall shrubs:	Dominant – *Melaleuca* spp. such as *M. acuminata* subsp. *acuminata*, *M. lanceolata*, *M. linguiformis*, *M. pauperiflora* subsp. *fastigiata*, *M. sheathiana* or *M. thyoides* Common – *Alyxia buxifolia*, *Exocarpos aphyllus* Others – *Acacia chrysella*, *Grevillea cagiana*, *G. huegelii*
Mid shrubs:	Dominant – *Melaleuca eleuterostachya*, *M. teuthidoides* or juvenile *Melaleuca* spp. dominant in the tall shrub stratum Common – *Phebalium* spp. Other – *Melaleuca undulata*
Low shrubs:	Dominant – not present as a recognisable stratum Common – *Acacia acoma*, *Olearia muelleri* Other – *Rhagodia drummondii*

Other plant forms: Common – *Carpobrotus* spp. (succulent perennial herb), *Dianella revoluta* (perennial herb), *Lepidosperma drummondii* (sedge), *Lomandra effusa* (rush)

* Also known from Newbey and Hnatiuk (1988)

Priority flora

Phebalium drummondii (Priority 3) was recorded at one site.

Ecological disturbance

Most plants in PPWL are not particularly palatable or preferred by livestock. All observed examples of this habitat type occurred outside the pastoral estate, making it difficult to confidently assess grazing effects. The low relief, dense vegetation, presence of sand sheets and sporadic sheet flow suggests PPWL is not particularly susceptible to erosion.

Gradational associations

In some sections of playa plains, PPWL may transition into Lakeside (sand sheet) eucalypt woodland with shrubs (LSES, #64) as sand content increases because of proximity to lunettes. In the Youanmi South Zone where the playa plains of the Cheriton land system are marginal to the alluvial plains of the Forrestiana land system, PPWL may transition into Sand sheet mallee heath (SAMH, #41). In the Dundas, Nanambinia and Salmon Gums Mallee zones where playa plains border sheetwash plains and soils change from Yellow–brown shallow sandy duplex to Calcareous loamy earth or shallow loam, PPWL transitions into Eucalypt, false bluebush woodland (EFBW, #53) as *Cratystylis conocephala* (false bluebush) increases through the understorey, or Dense eucalypt, melaleuca forest (DEMF, #55).

Land systems

PPWL is the dominant habitat type in the Cheriton land system, a major habitat type in the Halbert land system and a minor habitat type in the Charlina and Dundas land systems.

A structurally mature mixed eucalypt woodland consisting of *Eucalyptus salicola* (salt gum), *E. salmonophloia* (salmon gum) and *E. transcontinentalis* (redwood) over mixed melaleucas on a Yellow–brown shallow sandy duplex soil on a playa plain in the Cheriton land system

Dense regrowth stand of mallee woodland consisting of *Eucalyptus alipes* and *E. salicola* among groves of mixed melaleucas on a Yellow–brown shallow sandy duplex soil on a playa plain in the Cheriton land system

63 Lakeside (sand sheet) mallee woodland with spinifex (LSMX)

Sampling

5 inventory sites, 33 traverse points

General information

LSMX is described for the first time. It is a dominant habitat type on lunettes, dunes and back slope sand sheets associated with salt lakes and playas. This habitat type is typically found on the south, east and occasionally north sides of the salt lakes. Landforms result from the accumulation of eolian deposits that originate from lacustrine sources. The source material is blown out of salt lakes during dry periods, which causes the lakes to deflate until they become inundated again. Wave action then sorts the surficial lacustrine sediments, which blow out again during the next dry period. Soils typically consist of Deep red sand or Red sandy earth derived from reworked, windblown calcareous parna, clay, silt and sand particles.

LSMX includes the former mallee–spinifex associations described as Sandplain mallee, spinifex woodland (SAMA) in the Kambalda survey; which Payne et al. (1998a) considered similar to the SAMA subtype, as described in the north-eastern Goldfields (Pringle et al. 1994). Despite some similarities in composition, LSMX and SAMA are recognised as different habitat types because LSMX is associated with the margins of salt lakes on reworked lacustrine deposits, and SAMA occurs on extensive sandplains on red, deep, siliceous sands largely derived in situ.

Physiognomy and composition of vegetation

LSMX typically consists of a moderately close (>20–30% PFC), low (<8 m) eucalypt woodland over an understorey of *Triodia scariosa* (spinifex) of variable density. The woodland is frequently dominated by *Eucalyptus concinna* (Victoria Desert mallee), though occasionally other eucalypts, such as *E. gracilis* (white mallee), *E. horistes* (pointed-bud mallee) or *E. platycorys* (Boorabbin mallee), may dominate. The tall shrub stratum is variably developed. The mid and low shrub strata are often poorly developed and may be absent when spinifex is dense and contiguous.

The dominant and common species by strata:

Mallees:	Dominant – *Eucalyptus* spp. such as *E. concinna*, *E. gracilis**, *E. horistes*, *E. incrassata**, *E. leptophylla**, *E. platycorys*
Tall shrubs:	Dominant – variable Common – *Eremophila interstans* subsp. *interstans, Santalum acuminatum* Others – *Acacia ligulata*, *Exocarpos aphyllus*
Mid shrubs:	Dominant – rarely present as a recognisable stratum Common – *Acacia hemiteles*, *Eremophila caperata*, *E. scoparia*, *Scaevola spinescens*, *Senna artemisioides* subsp. *filifolia* Others – *Grevillea huegelii**, *Phebalium canaliculatum*
Low shrubs:	Dominant – rarely present as a recognisable stratum Common – *Scaevola spinescens*, *Westringia rigida* Others – *Coopernookia strophiolata*, *Daviesia aphylla*, *Grevillea plurijuga* subsp. *plurijuga*
Perennial grasses:	Dominant – *Triodia irritans*, *T. scariosa*
Other plant forms:	Occasional – *Dianella revoluta* (perennial herb), *Lepidosperma drummondii** (sedge), *Lomandra effusa* (rush)

* Also known from Beard (1975); Newbey and Hnatiuk (1984, 1988); Keighery et al. (1992); Keighery et al. (1993)

Ecological disturbance

LSMX has very low pastoral value and is generally unaffected by grazing. Spinifex hummock grass and most of the shrubs associated with this habitat are not favoured by livestock. Erosion is rarely a problem because the dense spinifex coverage protects sandy soils from winds blowing across lake surfaces. Wind erosion is only a potential issue when soils are exposed after fire.

Gradational associations

On lunettes, dunes and sand sheets associated with salt lakes, LSMX transitions into Lakeside (sand sheet) eucalypt woodland with shrubs (LSES, #64) where spinifex is replaced by shrubs. On some sand sheets, a mosaic of intermediate forms between LSMX and LSES occurs. Elsewhere, LSMX is usually a distinctive habitat type with clearly defined boundaries.

Land systems

LSMX is the dominant habitat type in the Lakeside land system and a minor habitat type in the Carnegie, Cronin, Lefroy, Rowles and Yardina land systems.

Lakeside mallee woodland dominated by *Eucalyptus platycorys* (Boorabbin mallee) over with spinifex on a Red sandy earth soil in the Lakeside land system

64 Lakeside (sand sheet) eucalypt woodland with shrubs (LSES)

Subtype: Lakeside (sand sheet) *Bossiaea* shrubland (LSBS)

Sampling

LSES: 22 inventory sites, 44 traverse points

LSBS: 4 inventory sites

General information

LSES is described for the first time. It is similar to Lakeside (sand sheet) mallee woodland with spinifex (LSMX), with both communities broadly occupying similar landforms adjacent to salt lakes and playas. LSES, like LSMX, is usually found on the south and east sides of salt lakes on generally sandy and calcareous surfaces formed from windblown lacustrine deposits. However, though both communities occur on sand sheets, LSES is more common to the back slope sand sheets between the lacustrine eolian deposits and the adjacent alluvial and sheetwash plains or in the drainage tracts between. LSMX is more likely to be associated with lunettes and dunes. While some sand sheets have a mosaic of intermediate forms between LSES and LSMX, typically the communities can be differentiated by their understorey: the lower strata of LSES typically consists of mixed shrubs, while LSMX is dominated by spinifex hummock grasses.

A subtype of LSES is Lakeside (sand sheet) *Bossiaea* shrubland (LSBS). While the physiognomy and composition of the LSBS association is similar to LSES, it is distinguished by the dominance of *Bossiaea walkeri* in the mid shrub stratum. LSES was treated as the major habitat type and LSBS was used as a component type to provide species-specific information while in the field.

Eucalyptus salmonophloia (salmon gum) and *E. transcontinentalis* (redwood) over an *Eremophila caperata* understorey on a Calcareous shallow loam soil in the Doney land system

Lakeside (sand sheet) *Bossiaea* shrubland on a low dune on a Brown sandy earth soil in the Lake Deborah land system

Eolian sands have variable depth and form dunes to sand sheets that overlie variable alluvial and colluvial substrates. Consequently, there is much edaphic variability of soils of LSES which range from Red or Yellow–brown, deep sands, sandy earths or shallow sandy duplexes to Calcareous loam or loamy earth. Most commonly, the soil is Calcareous sandy earth and Calcareous gravelly deep sand, becoming Calcareous loamy earth. Where sodicity and salinity may have affected soil development, Alkaline sandy duplex soils form.

Physiognomy and composition of vegetation

LSES consists of a moderately close to closed (≥20% PFC) eucalypt woodland over a variably developed tall and mid shrubland. The woodland physiognomy and composition are variable, depending on proximity to lacustrine landforms, soil composition and depth. The uppermost stratum ranges from trees over 15 m tall, frequently dominated by *Eucalyptus transcontinentalis* (redwood), to low mallees (<10 m), with *E. oleosa* subsp. *oleosa* frequently the dominant mallee. The tall and mid shrub strata range from scattered to moderately close (>10–30% PFC), and are frequently dominated by *Eremophila caperata*, or *Bossiaea walkeri* in LSBS. The low shrub stratum is usually very scattered to scattered (5–20% PFC), though occasionally moderately close (>20–25% PFC). Some halophytes may be present, but this habitat typically does not support a Chenopodiaceae complex. Perennial grasses are usually absent, except for scattered spinifex hummocks. Perennial herbs and rushes, such as *Dianella revoluta* (blueberry lily) and *Lomandra effusa* (scented matrush), are common.

The dominant and common species by strata:

Trees:	Dominant – *Eucalyptus* spp.; often *E. transcontinentalis*, occasionally *E. salicola*, *E. salmonophloia*, *E. urna* Common – *E. lesouefii*, *E. salubris*, *E. transcontinentalis* (when other species are dominant) Others – *Callitris columellaris**, *Casuarina pauper*
Mallees:	Dominant – *Eucalyptus* spp.; often *E. oleosa* subsp. *oleosa*, occasionally *Eucalyptus concinna*, *E. eremophila*, *E. griffithsii*, *E. platycorys*, *E. yilgarnensis* Common – *E. oleosa* subsp. *oleosa*, *E. yilgarnensis* (west and central survey area) Other – *Eucalyptus gracilis*
Tall shrubs:	Dominant – variable; often *Eremophila caperata*, occasionally *Melaleuca* spp. such as *M. acuminata*, *M. eleuterostachya*, *M. hamata*, *M. pauperiflora* subsp. *fastigiata* Common – *Acacia colletioides*, *A. nyssophylla*, *Exocarpos aphyllus*, *Santalum acuminatum* Others – *Alyxia buxifolia*, *Jacksonia arida*
Mid shrubs:	Dominant – *Eremophila caperata*; occasionally *Bossiaea walkeri* Common – *Acacia hemiteles*, *Eremophila decipiens*, *E. ionantha*, *E. scoparia*, *Halgania andromedifolia*, *Scaevola spinescens*, *Senna artemisioides* subsp. *filifolia* Others – *Cratystylis conocephala*, *Grevillea huegelii*
Low shrubs:	Dominant – variable; often *Scaevola spinescens*, *Westringia rigida* Common – *Acacia acoma*, *Grevillea acuaria*, *Olearia muelleri*, *Scaevola spinescens*, *Westringia rigida* Others – *Gunniopsis quadrifida*, *Phebalium* spp., *Rhagodia drummondii*
Perennial grasses:	Dominant – rarely present as a recognisable stratum Common – *Triodia scariosa*
Other plant forms:	Common – *Dianella revoluta* (perennial herb), *Lomandra effusa* (rush) Occasional – *Lepidosperma drummondii* (sedge)

* Also known from Newbey and Hnatiuk (1984, 1988); Newbey et al. (1995)

Priority flora

Acacia bartlei (Priority 3) and *Phebalium drummondii* (Priority 3) were recorded at one site each.

Ecological disturbance

LSES is generally unaffected by grazing because most shrubs are not favoured by livestock. The dense coverage of vegetation largely protects and buffers these habitats from wind. Wind erosion may become an issue when soils are exposed after fire, though prompt emergence of regrowth usually restores stability.

Gradational associations

LSES transitions into LSMX where spinifex begins to dominate the understorey. Where windblown lacustrine deposits from the back slopes of lunettes and sand sheets are incorporated into adjacent plains, LSES often transitions into Plain eucalypt, eremophila woodland (PEEW, #59). Here, *Eremophila caperata* is replaced by *E. scoparia* (broom bush) in the tall and mid shrub strata. Where mallees decrease from the uppermost stratum on sand sheets close to lake margins, LSES may transition into Sandy bank lake shrubland (SBLS, #69).

Land systems

LSES is a major habitat type in the Cronin, Lakeside and Wangine land systems and a minor habitat type in the Carnegie, Cheriton, Deadman, Doney, Forrestania, Holland, Lake Deborah, Lefroy, Rowles, Sharpe and Yardina land systems.

Uncommon habitats in Depositional plain woodland over shrubland habitat group

65 Lakeside dune *Callitris* woodland (LDCW)

3 inventory sites

General information

LDCW is described for the first time. It is uncommon, associated with dunes and lunettes adjacent to salt lakes and playas, and characterised by the presence of *Callitris* species. Being less gypsiferous than kopi dunes these eolian deposits typically consist of Calcareous sandy earth soils and, less commonly, Red deep sand soils.

Physiognomy and composition of vegetation

The physiognomy may be determined by the size, shape and orientation of the eolian deposit it resides on, with 2 structural forms of similar composition encountered. LDCW can occur as a scattered (>10–15% PFC) low, *Callitris* woodland, spread across the entirety of broad dunes and lunettes, with a similarly scattered understorey consisting primarily of halophytic shrubs and infrequent non-halophytic shrubs. Alternatively, LDCW can occur as moderately close (25–30% PFC) *Callitris* groves, typically confined to the crests of narrow lunettes, with the grove understorey consisting of a scattered to moderately close (>15–25% PFC) mix of halophytic and non-halophytic shrubs. Outside of the grove plants are isolated and scattered. The *Callitris* overstorey consists of either *C. columellaris* (white Cypress pine) or *C. preissii* (Rottnest Island pine). *Acacia aneura* (mulga) and *Eremophila miniata* (kopi poverty bush) may also be present in the tall shrub strata in the north of the survey. *Dodonaea viscosa* (sticky hopbush) is frequently present as isolated individuals. *Atriplex vesicaria* (bladder saltbush) and *Maireana pyramidata* (sago bush) are common in the low and mid shrub strata, with *Enchylaena tomentosa* (ruby saltbush) and *Rhagodia drummondii* (lake-fringe rhagodia) – both key decreasers – being particularly common within the groves.

Callitris columellaris (white Cypress pine) on a dune of Red deep sand soil in the Lefroy land system

Ecological disturbance

Grazing impact is influenced by accessibility to fresh water. If the drinking water is fresh, continuous grazing pressure may result in a decrease in palatable chenopods, such as *Atriplex vesicaria*, *Enchylaena tomentosa* and *Rhagodia drummondii*.

Gradational association

Dune and lunette edges are usually clearly defined and the boundary with adjacent halophytic communities or lake bed is obvious. On the back slopes of these eolian deposits, LDCW may transition into Lakeside (sand sheet) mallee woodland with spinifex (LSMX, #63), Lakeside (sand sheet) eucalypt woodland with shrubs (LSES, #64) or Sandy bank lake shrubland (SBLS, #69).

Land systems

LDCW is a minor habitat type in the Carnegie, Lefroy and Ponton land systems.

66 Lakeside dune proteaceous heathland (LDPH)

Sampling

2 inventory sites

General information

LDPH is described for the first time but is only provisionally described because there was insufficient sampling. It is associated with dunes adjacent to occluded salt lakes and playas in the far south of the survey. The soils of the dunes consist of Yellow deep sand and the intervening swales have a similar soil that is paler, sometimes forming Pale deep sand.

Physiognomy and composition of vegetation

LDPH comprises moderately close to closed (≥25% PFC) thickets of banksia and grevillea, with infrequent stands of emergent eucalypt mallees. Habitat structure appears to be closely related to time elapsed since fire. Heath grading upwards into tall scrub usually occurs closer to the lake margin and the foredune slope, with mallees becoming more frequent on the dune crest and back slope. Perennial grasses are absent.

Dune crest supporting a semi-mature cohort of emergent mallees in a proteaceous-dominated heath-scrubland in a recovery phase after fire

The dominant and common species by strata:

Trees:	Dominant – rarely present other than as emergents Common – *Banksia media*
Mallees:	Dominant – various *Eucalyptus* spp. Common – *Eucalyptus* sp. North Balladonia Others – *Eucalyptus conglobata**, *E. eremophila**, *E. fraseri**, *E. goniantha**, *E. incrassata**, *E. kessellii* subsp. *kessellii*
Tall shrubs:	Dominant – variable; often *Banksia* spp., *Grevillea* spp. Common – *Acacia triptycha*, *Banksia media* Others – *Acacia diaphana* (P1), *Dodonaea viscosa* subsp. *angustissima*, *Exocarpos sparteus*, *Grevillea aneura* (P4), *Hakea multilineata**
Mid shrubs:	Dominant – variable; heath shrubs; often Myrtaceae Common – *Rinzia icosandra* Others – *Adenanthos ileticos* (P4), *Beyeria lechenaultii**, *Melaleuca teuthidoides**, *Philotheca rhomboidea*
Low shrubs:	Dominant – variable; heath shrubs Others – *Boronia coerulescens**, *Calytrix duplistipulata*, *Conostephium drummondii**, *Darwinia luehmannii** (P2), *D. polycephala* (P4), *Hemigenia teretiuscula*, *Hibbertia gracilipes*, *Hybanthus epacroides**, *Persoonia teretifolia**, *Pimelea erecta**, *Pultenaea elachista**, *Stachystemon brachyphyllus**, *Verticordia vicinella*
Other plant forms:	Occasional – *Cassytha aurea* (climber), *Goodenia scapigera* subsp. *scapigera* (perennial herb), *Lomandra micrantha** (rush)

* Also known from Beard (1975); Keighery et al. (1993)

Priority flora

Darwinia polycephala (Priority 4) and *Grevillea aneura* (Priority 4) were recorded at two sites. *Acacia diaphana* (Priority 1) and *Adenanthos ileticos* (Priority 4) were recorded at one site each. Keighery et al. (1993) also recorded *Darwinia luehmannii* (Priority 2).

Ecological disturbance

The mechanisms of disturbance in LDPH have not been investigated in detail. Wind erosion may result when fire reduces perennial vegetation.

Gradational associations

The ecotone between the dune fringe and lake bed is clearly defined. On the peripheral dune back slope, LDPH transitions into Eucalypt mallee, melaleuca shrubland (EMMS, #68) where sand sheets merge into the surrounding plains.

Land systems

LDPH is a minor habitat type in the Buraminya and Burdett land systems.

67 Lakeside sandy bank casuarina shrubland (LSCS)

Sampling

1 inventory site, 6 traverse points

General information

LSCS was first described in the Kambalda survey (Payne et al. 1998a). It is an uncommon habitat associated with sand sheets and dunes adjacent to salt lakes and playas. Soil is Red deep sand.

Physiognomy and composition of vegetation

LSCS consists of very scattered (>2.5–10% PFC) *Casuarina pauper* (black oak) trees among a scattered (>10–15% PFC) tall shrubland dominated by *Acacia* spp. (such as *A. acuminata, A. hemiteles*) and *Eremophila* spp. (such as *E. decipiens* subsp. *decipiens, E. miniata, E. scoparia*). *Alyxia buxifolia* (dysentery bush), *Exocarpos aphyllus* (leafless ballart) and *Jacksonia arida* are occasionally present. The mid and low shrub strata may contain scattered *Cratystylis conocephala* (false bluebush), *C. microphylla* (small-leaved grey bush), *Gunniopsis quadrifida* (Sturts pigface), *Olearia pimeleoides* (pimelea daisybush) and *Scaevola spinescens* (currant bush). Chenopods – such as *Enchylaena tomentosa* (ruby saltbush), *Maireana glomerifolia* (ball leaf bluebush), *M. pyramidata* (sago bush), *M. sedifolia* (pearl bluebush), *Rhagodia drummondii* (lake-fringe rhagodia) and *Tecticornia* spp. (samphire) – may be present but are usually infrequent. Isolated tussocks of *Austrostipa elegantissima* (feather speargrass) and clumps of *Lomandra effusa* (scented matrush) may also be present.

Ecological disturbance

Not much is known. Disturbance events affecting Sandy bank lake shrubland (SBLS, #69) are likely to have similar effects on LSCS.

Gradational associations

Where *Casuarina pauper* decreases from the overstorey, the remaining understorey has physiognomic and compositional similarities to SBLS. Away from lake country with shallowing soils and *C. pauper* increasing in prominence, LSCS may transition into Calcareous casuarina, acacia shrubland or woodland (CCAS, #80). Elsewhere boundaries are usually clearly defined.

Land systems

LSCS is a minor habitat type in the Lefroy land system.

68 Eucalypt mallee, melaleuca shrubland (EMMS)

Sampling

2 inventory sites

General information

EMMS is described for the first time but is only provisionally described because there was insufficient sampling. It occurs in the southernmost areas of the survey. EMMS is associated with very gently undulating plains on weathered Cenozoic sediments with sand sheets of varying depth. Soils are Alkaline yellow–brown shallow (or deep) sandy duplexes.

Our ability to describe the physiognomy and composition of vegetation for EMMS was affected by extensive, recent (<10 years) bushfires within this habitat at the time of survey. In the recently burnt areas, resultant regrowth tended to be dominated by dense stands of immature eucalypt saplings, with no suitable reference material available for collection. Also restricting data acquisition was the limited access to much of this area, further constrained by wet weather and bushfires during the survey. Inventory information collected by the WA Museum (Keighery et al. 1993) in 1990 during the biological survey of the Norseman–Balladonia area provided complementary information.

Physiognomy and composition of vegetation

EMMS habitats accessible during our survey were limited to areas that had been extensively burned and were in various stages of regrowth after fire. The variability in the structure and density of the mallee and associated flora correlates well with time since the last fire. Information from Keighery et al. (1993) suggests mature stands of EMMS occur as a mosaic of moderately close to closed (>20% PFC), low (<10 m), mallee woodland with closed (>50% PFC) thickets of *Melaleuca* species. The mid and low shrub strata are variably developed and consist of non-halophytic shrubs. Perennial grasses are absent.

The dominant and common species by strata:

Mallees:	Dominant – variable
	Common – *Eucalyptus conglobata**, *E. eremophila**, *E. transcontinentalis** (mallee form)
	Others – *Eucalyptus indurata**, *E. leptocalyx*, *E. tortilis*, *E. tumida**
Tall shrubs:	Dominant – variable; occasionally *Melaleuca teuthidoides**
	Common – *Exocarpos aphyllus*, *Melaleuca eleuterostachya**, *M. lateriflora**, *M. teuthidoides**, *M. uncinata**
	Others – *Melaleuca acuminata* subsp. *acuminata*, *M. cucullata**, *M. glaberrima**, *M. linguiformis*, *M. quadrifaria**, *Santalum acuminatum**
Mid shrubs:	Dominant – not present as a recognisable stratum
	Others – *Melaleuca bromelioides**, *Nematolepis phebalioides**
Low shrubs:	Dominant – not present as a recognisable stratum
	Others – *Acacia lachnophylla*, *A. merrallii**, *Cyathostemon ambiguus**, *Daviesia* spp.*, *Grevillea huegelii**, *G. pauciflora**, *Hibbertia gracilipes*, *Logania stenophylla*, *Microcybe pauciflora**, *Olearia muelleri**, *O. ramosissima**, *Pultenaea elachista**, *Scaevola bursariifolia*, *S. spinescens*, *Wilsonia humilis*
Other plant forms:	Occasional – *Cassytha aurea** (climber), *C. melantha** (climber)

* Also known from Keighery et al. (1993)

Priority flora

Keighery et al. (1993) recorded *Darwinia luehmannii* (Priority 2) and *Eucalyptus creta* (Priority 3).

Ecological disturbance

The mechanisms of disturbance have not been investigated in detail. Disturbance events affecting Sand sheet mallee heath (SAMH, #41) are likely to have similar effects on EMMS.

Gradational associations

The transition from the Salmon Gums Mallee Zone into the south of the Dundas and Nanambinia zones is marked by an edaphic change. Where Yellow–brown sandy duplex over alkaline subsoil changes into Calcareous loamy earth, Red loamy earth or shallow loamy duplex soils, the predominance of EMMS transitions into Eucalypt, teatree woodland (ETTW, #54), initially as a mallee matrix with patches of woodland until ETTW dominates. Extensive fires during the survey period complicated the differentiation between these woodlands because the resprouting after fire results in physiognomic similarities between mallee-dominated habitats and burnt eucalypt woodland.

Within the expanse of gently undulating plains, EMMS transitions into Lakeside dune proteaceous heathland (LDPH, #66) where sand sheets merge with lacustrine dunes near occluded salt lakes and playas.

Land systems

EMMS is a major habitat type in the Buraminya land system and a minor habitat type in the Burdett and Cowalinya land systems.

J Depositional plain mixed halophyte shrubland habitats

These habitat types occur in depositional landscapes and are characterised by a low shrub stratum dominated by halophytic shrubs. Such habitat types extend from the Pilbara (Van Vreeswyk et al. 2004) through to the Nullarbor (Waddell et al. 2010) and are generally confined to the margins of lake beds or in saline low-lying depressions within undulating plains. The most common genera are *Atriplex* (saltbushes), *Maireana* (bluebushes) and *Tecticornia* (samphire) which belong to the Chenopodiaceae family, but others such as *Frankenia* (Frankeniaceae), *Gunniopsis* (Aizoaceae) and *Lycium* (Solanaceae) also occur frequently in many habitat types. These halophytic shrubs typically show significant tolerance to saline conditions and resistance to water stress. Annual and biennial growth of grasses (species of *Aristida*, *Austrostipa*, *Eragrostis*, *Rytidosperma*), and herbs (Asteraceae, *Sclerolaena* spp., *Sida spodochroma*) in cooler months, can be considerable in favourable seasons.

These chenopod-dominated plains are most commonly associated with duplex soils but can also occur on clay soils. Soil stability varies according to the intensity of run-on received. The alluvial plains adjacent to salt lakes are usually quite stable because they are nearly level and subject to relatively low energy surface flows.

This group has some of the highest pastoral value for shrublands in the southern rangelands, and in many situations, the habitats are susceptible to degradation through reduced plant cover and consequent erosion. Research in the north-eastern Goldfields on chenopod shrublands on alluvial plains provides information relevant to this habitat type group because of the similar soil characteristics and species composition. Hacker (1979) found that soil characteristics, such as salinity, varied considerably within habitats and influenced floristic heterogeneity. Through preferential grazing by livestock, floristic heterogeneity can be reduced and consequently vegetation patches develop. Hacker also recognised that small scalds, which are naturally present in ungrazed areas, expand when shrub cover is reduced by grazing pressure. The expansion of scalded areas represented the crossing of a threshold from which regeneration could not be achieved by manipulating grazing pressure alone. To avoid this form of degradation, Hacker emphasised the need for pastoral managers to maintain shrub cover well above critical thresholds.

69 Sandy bank lake shrubland (SBLS)

Sampling

6 inventory sites, 66 traverse points

General information

SBLS was described in the north-eastern Goldfields (Pringle et al. 1994) and the Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b) surveys. It occurs on sand banks on alluvial plains surrounding salt lakes, with varying degrees of development and regularity of pattern. Sand banks are formed when sand, transported by wind and water, is reworked by high energy sheet flow processes. Their alignment is influenced by the slope and prevailing winds between periods of lake inundation. Soils are generally Red deep sand, Red sandy earth or, occasionally, Alkaline red shallow (or deep) sandy duplex soils on lower banks and Saline soil in landscape depressions.

Physiognomy and composition of vegetation

SBLS is represented by 2 floristic components: a non-halophytic component associated with non-saline, coarse-textured soils, and a halophytic low shrub component associated with duplex soils. The morphology of the sandy banks appears to influence the relative proportions of the components. The non-halophytic shrub component features more prominently on the higher banks where deeper sandy soils provide the associated vegetation with increased water availability through enhanced infiltration, deeper storage and reduced evaporation rates. Chenopods typically dominate the lower banks and bank margins, possibly due to the development of duplex soils and increasing soil salinity associated with proximity to lake margins. This variability is reflected in the diverse range of form and composition this habitat type may show.

SBLS occurs as a scattered to moderately close (>10–25% PFC) shrubland with a subordinate perennial grass component. The tall and mid shrub strata generally dominate, with prominent low shrubs. Trees and perennial grasses feature less commonly. Perennial grasses appear to be less conspicuous in SBLS within the southern Goldfields, than in the north-eastern Goldfields. The higher winter rainfall in the south may favour shrubs over grasses in the competition for ecological niches, though with climate change this scenario may change.

Sandy bank lake shrubland on a Red shallow sandy duplex soil in the Lefroy land system

The dominant and common species by strata:

Trees:	Dominant – rarely present other than as emergents Common – *Acacia aneura*, *Pittosporum angustifolium*
Tall shrubs:	Dominant – variable; often *Acacia* spp., *Eremophila* spp. Common – *Acacia aneura*, *A. burkittii*, *A. tetragonophylla*, *Dodonaea viscosa* subsp. *angustissima*, *Eremophila miniata*, *Exocarpos aphyllus*, *Hakea preissii* (KI) Others – *Acacia oswaldii*, *A. ramulosa* var. *ramulosa*, *Eremophila longifolia*, *E. oldfieldii*
Mid shrubs:	Dominant – variable Common – *Eremophila scoparia*, *Scaevola spinescens*, *Senna artemisioides* subsp. *filifolia (KI)* Others – *Cratystylis subspinescens*, *Melaleuca halmaturorum*
Low shrubs:	Dominant – *Enchylaena tomentosa (KD)*, *Maireana pyramidata*, *Rhagodia drummondii* (KD) Common – *Atriplex vesicaria* (KD), *Frankenia* spp., *Gunniopsis quadrifida*, *Maireana sedifolia*, *M. triptera*, *Ptilotus obovatus*, *Scaevola spinescens*, *Solanum lasiophyllum*, *S. orbiculatum*, *Tecticornia doliiformis* Others – *Atriplex bunburyana* (KD), *A. stipitata*, *Lycium australe*, *Maireana georgei* (KD)
Perennial grasses:	Dominant – rarely present as a recognisable stratum Common – *Austrostipa elegantissima* Others – *Austrostipa scabra*, *Eragrostis dielsii*, *Eriachne helmsii*, *Rytidosperma caespitosum*
Other plant forms:	Occasional – *Leichhardtia australis* (climber)

Ecological disturbance

The natural variability in relation to the 2 floristic components of this habitat makes it difficult to assess resource condition. The most sensitive indicators of grazing impact in SBLS are in the palatable chenopod low shrub component. Under heavy grazing palatable shrubs, such as *Atriplex bunburyana* (silver saltbush), *A. vesicaria* (bladder saltbush) and *Maireana georgei* (George's bluebush), may decrease. These changes may allow a secondary succession involving an increase in *Maireana pyramidata* (sago bush) and unpalatable species, such as *Hakea preissii* (needle bush) and *Solanum orbiculatum* (wild tomato). Rabbits frequently establish warrens in this habitat, causing further degradation.

Gradational associations

Sand bank edges are usually clearly defined, making the boundaries with adjacent halophytic communities distinct. As non-halophytic shrub species are increasingly replaced on the lower slopes by halophytic species and the soils become prone to waterlogging and salinity SBLS typically borders Plain mixed halophyte shrubland (PXHS, #70), Samphire shrubland (SAMP, #71), Bladder saltbush low shrubland (BLSS, #72) or Frankenia low shrubland (FRAN, #74). Where sand banks coalesce into sand sheets, SBLS commonly transitions into Lakeside (sand sheet) mallee woodland with spinifex (LSMX, #63) or Lakeside (sand sheet) eucalypt woodland with shrubs (LSES, #64) or merges into adjacent plains grading into Plain eucalypt, eremophila woodland (PEEW, #59).

Land systems

SBLS is a major habitat type in the Carnegie, Lake Deborah and Lefroy land systems and a minor habitat type in the Ponton and Rowles land systems.

70 Plain mixed halophyte shrubland (PXHS)

Sampling

9 inventory sites, 138 traverse points

General information

PXHS was described as a Mixed halophytic shrubland (MXHS) in the Murchison River catchment (Curry et al. 1994) and as a PXHS in the north-eastern Goldfields (Pringle et al. 1994), Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b), Pilbara (Van Vreeswyk et al. 2004) and WA Nullarbor (Waddell et al. 2010) surveys. PXHS is found throughout the survey area. It is common to many saline alluvial plains occurring adjacent to salt lakes.

PXHS usually consists of a mosaic of subcommunities, all with different dominant species, but often at a scale too fine for differentiation. The subcommunities are similar to other chenopod habitat types dominated by single species, such as Samphire low shrubland (SAMP, #71), Bladder saltbush low shrubland (BLSS, #72), Plain sago bush shrubland (PSAS, #73) and Frankenia low shrubland (FRAN, #74). These differences in subcommunities reflect subtle patterns relating to soil hydrology and salinity. PXHS is also found on alluvial plains carrying flow to lake country, and isolated alluvial plains and valley floors within upland regions. Soils are characteristically saline and red and are otherwise variable. They are often duplex or have clay texture from the surface.

Physiognomy and composition of vegetation

PXHS commonly occurs as scattered to close (15–50% PFC) low shrublands, with infrequent stands of mid shrubs and isolated tall shrubs. In some instances, the low shrub stratum is without any other conspicuous strata and may be closed (≥50% PFC). Often the low shrub stratum consists of a mosaic of different subcommunities, each with different suites of prominent or dominant species in patches too small to differentiate as separate habitat types.

Plain mixed halophyte shrubland in a saline alluvial plain in the Moorebar land system

The dominant and common species by strata:

Tall shrubs:	Dominant – rarely present other than as emergents Common – *Pittosporum angustifolium* Others – *Acacia tetragonophylla*, *Exocarpos aphyllus*, *Hakea preissii* (KI), *Santalum spicatum*
Mid shrubs:	Dominant – *Cratystylis subspinescens* (KD), *Maireana pyramidata* Common – *Atriplex nummularia* subsp. *spathulata* Others – *Eremophila decipiens*, *E. miniata*, *E. scoparia*, *Scaevola spinescens*, *Senna artemisioides* subsp. *filifolia* (KI)
Low shrubs:	Dominant – *Atriplex vesicaria* (KD), *Cratystylis subspinescens* (KD) Common – *Enchylaena tomentosa* (KD), *Frankenia* spp., *Gunniopsis quadrifida*, *Lycium australe*, *Maireana sedifolia*, *M. tomentosa*, *M. triptera*, *Minuria cunninghamii*, *Ptilotus obovatus*, *Rhagodia drummondii* (KD), *Solanum lasiophyllum*, *Tecticornia doliiformis* Others – *Atriplex bunburyana* (KD), *A. stipitata*, *Chenopodium curvispicatum* (KD), *Maireana atkinsiana* (KD), *M. georgei* (KD), *M. platycarpa* (KD), *Scaevola spinescens*, *Solanum nummularium*
Perennial grasses:	Dominant – rarely present as a recognisable stratum Common – *Rytidosperma caespitosum*, *Eragrostis dielsii* Others – *Austrostipa elegantissima*, *A. scabra*
Other plant forms:	Common – *Sclerolaena diacantha* (perennial herb) Others – *Carpobrotus* spp., *Disphyma crassifolium* (succulent perennial herb), *Sida spodochroma* (perennial herb)

Ecological disturbance

Where good quality water is available, grazing pressure can lead to reductions in palatable plants. Curry et al. (1994) observed that excessive grazing reduces foliar cover and when a threshold is crossed, PXHS becomes susceptible to combinations of accelerated erosion and/or increases in unpalatable shrubs with invasive tendencies. Where PXHS has been previously described, it was found that the most sensitive indicator of grazing impact was the prominence of key decreaser species and, to a lesser extent, increaser species. Under heavy grazing pressure, palatable shrubs that tend to decrease include *Atriplex bunburyana* (silver saltbush), *A. vesicaria* (bladder saltbush), *Enchylaena tomentosa* (ruby saltbush), *Maireana atkinsiana* (bronze bluebush), *M. georgei* (George's bluebush) and *M. platycarpa* (shy bluebush). Increaser species include *Hakea preissii* (needle bush) and *Senna artemisioides* subsp. *filifolia* (desert cassia). With the loss of palatable plants, *Frankenia* species, *Maireana pyramidata* (sago bush) and *Tecticornia* species (samphire) can become dominant, reflecting secondary succession, although this is not a reliable indicator of condition. Discerning between grazing states and natural communities (i.e. FRAN, PSAS and SAMP) is difficult and requires local understanding of patterns of plant zonation and landscape position.

Saline subsoil makes it susceptible to scald development. As scalds coalesce, the ability to support plant growth is reduced. Loss of perennial species and scalds can result in accelerated soil loss through wind erosion. Pringle et al. (1994) found that the extent of cryptogamic crusting of the soil surface was significantly lower at grazed sites than reference sites, which increases susceptibility to erosion (Tongway and Greene 1989; Tongway 1994).

Gradational associations

Near salt lakes, PXHS is part of a complex of subcommunities that form a tight mosaic dominated by various low shrub species. PXHS transitions upslope into *Maireana pyramidata*-dominated PSAS and downslope into BLSS, SAMP or FRAN. Where sandy banks or kopi border salt lakes or fringe Ponton Creek, PXHS can be bordered by Sandy bank lake shrubland (SBLS, #69) or Kopi dune woodland (KOPI, #79). PXHS transitions into Plain eucalypt, halophytic woodland (PEHW, #60) as eucalypt species start to occur but soils remain saline. In sluggish drainage tracts through undulating plains based on weathered parent material PXHS is commonly bordered upslope by Calcareous pearl bluebush shrubland (CPBS, #31).

Land systems

PXHS is the major habitat in the Carnegie, Lefroy and Moorebar land systems and a minor habitat in the Bunyip, Gundockerta, Kanowna, Ponton and Rowles land systems. It also occurs infrequently on isolated alluvial plains and valley floors within some upland land systems.

71 Samphire shrubland (SAMP)

Sampling

8 inventory sites, 30 traverse points

General information

SAMP was described in the Carnarvon Basin (Payne et al. 1987), Murchison River catchment (Curry et al. 1994), North-eastern Goldfields (Pringle et al. 1994), Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b) and WA Nullarbor (Waddell et al. 2010) surveys. SAMP is associated with highly saline, gypsiferous soils fringing lake beds and sluggish drainage areas throughout the southern Goldfields. Less frequently, it is associated with shallow saline soils on weathered parent material, usually greenstone or volcaniclastic metasedimentary rocks. Soils are Saline soil, Salt lake soil, Calcareous loamy earth, Red shallow sandy or loamy duplexes, Red–brown or Grey non-cracking clays.


Two forms of Samphire shrubland: left) the more common form on saline, gypsiferous deposits across a playa lake; right) the less frequent form that occupies a saline stony plain and footslope

Physiognomy and composition of vegetation

SAMP contains a very scattered to close (5–50% PFC) low shrubland invariably dominated by *Tecticornia* species (samphire). *T. doliiformis* (samphire) and *T. halocnemoides* (shrubby samphire) were the most commonly recorded species, though in some locations other samphires are dominant, co-dominant or just infrequently present – *T. disarticulata*, *T. indica*, *T. peltata*, *T. pergranulata*. The low shrub layer is structurally dominant, and larger shrubs and trees are generally only present at habitat margins as gradations into other vegetation types. SAMP does not really have a unique flora assemblage; the composition is more determined by the unsuitability of habitats to support many of the more widely distributed chenopod species. These very distinctive physical environments are tolerated by only a few species that are physiologically adapted to waterlogging, high salinity and often gypsum.

Other common low shrubs are the key decreasers *Atriplex bunburyana* (silver saltbush), *A. vesicaria* (bladder saltbush) and *Cratystylis subspinescens* (Australian sage). Also common are *Disphyma crassifolium* (pigface), *Frankenia* spp. (such as *F. fecunda*, *F. interioris* var. *interioris*, *F. setosa*) and *Maireana* spp. (such as *M. pyramidata*, *M. radiata*, *M. triptera*).

Priority flora

Tecticornia flabelliformis (Priority 1) was recorded at one site.

Ecological disturbance

The high salt content in most plants, predominantly samphires, and the generally saline nature of these pastures renders this habitat unattractive to livestock. Pringle et al. (1994) noted livestock preferred less-saline pastures where available unless nearby water supplies are fresh and there is little else to eat. Some of the more palatable species, such as *Atriplex vesicaria* and *Sclerolaena diacantha* (grey bindii), which make up a minor component of this vegetation association, may be removed through grazing, though this is not a reliable indicator of condition because such species can be absent from ungrazed areas.

Samphire communities are among the initial colonisers of rangeland lacustrine environments. Where alluvial deposits accumulate over lake bed sediments, samphire communities encroach from lake margins onto lake beds to take advantage of changing edaphic conditions. This is a common process in closed saline depressions or occluded lakes.

When samphire communities are inundated for extended periods, they can be temporarily or permanently eliminated from lake margins. Re-establishment of samphire communities relies on periods without further inundation and the opportunity to overcome competition from established taller shrubs, which can survive inundation.

The lake margin of Rowles Lagoon: left) in 2013, a samphire shrubland grows; right) in 2016, the samphire has drowned by inundation, while melaleucas have survived

Gradational associations

SAMP populations associated with lake systems are often adjacent to Frankenia low shrubland (FRAN, #74) or Kopi dune woodland (KOPI, #79), or transition upslope of lake margins into Sandy bank lake shrubland (SBLS, #69), Plain mixed halophyte shrubland (PXHS, #70) or Bladder saltbush low shrubland (BLSS, #72) as soils become less prone to waterlogging, less saline or gypsiferous. Near lake beds in the west of the survey, associated with the Cronin land system, SAMP commonly transitions upslope into Lakeside (sand sheet) eucalypt woodland with shrubs (LSES, #64). In the east of the survey, in and adjacent to the Yardina land system, SAMP commonly transitions upslope into Eucalypt, false bluebush woodland (EFBW, #53).

Adjacent to sluggish drainage tracts with saline soils on weathered parent material, SAMP transitions into Plain eucalypt, halophytic woodland (PEHW, #60) as a eucalypt overstorey develops. Elsewhere, SAMP is a distinctive habitat type which has clearly defined boundaries.

Land systems

SAMP is the major habitat type in the Carnegie, Lake Deborah, Lefroy and Yardina land systems and a minor habitat type in the Cronin, Kanowna, Moorebar, Ponton and Rowles land systems.

72 Bladder saltbush low shrubland (BLSS)

Sampling

6 inventory sites, 16 traverse points

General information

BLSS is characterised by the dominance of *Atriplex vesicaria* (bladder saltbush). It was first described as a component of Saltbush shrubland in the Murchison River catchment survey (Curry et al. 1994) and then as a distinct habitat in the north-eastern Goldfields (Pringle et al. 1994) and Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b) surveys. BLSS habitat refers specifically to *A. vesicaria*-dominated alluvial plains in depositional landscapes. Despite a similar botanical appearance, there are other *A. vesicaria*-dominated habitat types in WA rangeland environments which, owing to the landscape setting and associated geomorphic processes, have been treated as separate habitat types. These include the *A. vesicaria*-dominated breakaway footslopes in the Sandstone, Yalgoo and Paynes Find area survey described as Breakaway footslope chenopod low shrublands (Payne et al. 1998b); the *A. vesicaria*-dominated plains on the Nullarbor (Waddell et al. 2010); and Atriplex low shrubland (ATLS, #76) described in this survey.

In the southern Goldfields, BLSS is typically found on 2 types of depositional landforms:

- It grows on Calcareous loamy earth and Calcareous shallow loam soils within narrow valley floors which lack defined drainage and meander through undulating plains on greenstones. When present in depressions and drainage floors, Shallow cracking or non-cracking clay soils dominate. Here, it can form almost homogenous stands and is not floristically diverse.
- It also grows on lunettes and near-level alluvial plains adjacent to salt lakes where bladder saltbush is the dominant species, though the habitat may also support a range of other halophytic shrubs as well. The soils are sandy-surfaced, red deep duplex soils which are non-saline at the surface but increase in salinity with depth, or, in occluded lake systems are Red sandy earth and Brown loamy earth, both with saline subsoil.

Atriplex vesicaria (bladder saltbush) low shrubland on a lunette in the Hope land system

Physiognomy and composition of vegetation

BLSS comprises a scattered to closed (≥10% PFC) low shrubland of *Atriplex vesicaria*, usually without tall shrubs or trees.

The dominant and common species by strata:

Mid shrubs:	Dominant – rarely present as a recognisable stratum Others – *Atriplex nummularia* subsp. *spathulata*, *Eremophila decipiens*, *Maireana pyramidata*
Low shrubs:	Dominant – *Atriplex vesicaria* (KD) Others – *Enchylaena tomentosa*, *Frankenia* spp., *Gunniopsis quadrifida*, *Lycium australe*, *Maireana atkinsiana* (KD), *M. georgei* (KD), *M. platycarpa* (KD), *M. sedifolia*, *M. tomentosa*, *M. triptera*, *Rhagodia drummondii*
Perennial grasses:	Others – *Austrostipa elegantissima*, *A. scabra*, *Eragrostis dielsii*, *Rytidosperma caespitosum*
Other plant forms:	Other – *Sclerolaena diacantha* (perennial herb)

Ecological disturbance

Atriplex vesicaria responds to moisture stress by shedding its leaves but will recover quickly in response to rainfall and soil moisture conditions that stimulate germination. During this recovery phase, it needs protection from grazing to allow germinant establishment and for mature plants to regain vigour and set seed. Sustained heavy grazing is likely to reduce perennial vegetation cover as well as reducing other palatable species, such as *Maireana atkinsiana* (bronze bluebush), *M. georgei* (George's bluebush) and *M. platycarpa* (shy bluebush). Reducing these species may result in BLSS becoming indistinguishable from other chenopod communities because generalist species, such as *M. pyramidata* (sago bush) and *M. triptera* (three-winged bluebush), become dominant or the community is encroached by species such as *Hakea preissii* (needle bush), which is an invader of degraded chenopod alluvial plains communities.

Some areas associated with greenstone formations have been significantly affected by logging which has altered some Plain eucalypt, saltbush woodland (PESW, #58) habitats into BLSS. From woodlands with a low shrub understorey, these heavily logged areas are now open shrublands. In some areas, trees have not regenerated to previous populations. In these instances, BLSS is a consequence of logging; however, BLSS on lake margins is a natural association and not considered a result of logging (Payne et al. 1998a). Other threats to *A. vesicaria* include its lack of fire tolerance and inability to regenerate after burning (Graetz and Wilson 1984; Waddell et al. 2010).

Areas in good condition are characterised by healthy cryptogamic crusting. This crust enhances soil stability, and its fragmentation may indicate that current grazing pressure is high.

Gradational associations

On duplex soils on alluvial plains associated with salt lakes and tributary alluvial tracts, BLSS often transitions into Plain mixed halophyte shrubland (PXHS, #70); it is regularly found in zonations and mosaics with species of *Tecticornia* (samphire) and *Frankenia*.

In greenstone-dominated landscapes, BLSS commonly transitions out of depressions and narrow valley floors up onto marginal slopes occupied by Calcareous pearl bluebush shrubland (CPBS, #31), or onto plains supporting PESW (#58) and Plain eucalypt, bluebush woodland (PEBW, #52).

Land systems

BLSS is a major habitat type in the Hope land system and a minor habitat type in the Carnegie, Gundockerta, Lefroy, Nyanga, Woolibar, Woorlba and Yardina land systems.

73 Plain sago bush shrubland (PSAS)

Sampling

10 inventory sites, 125 traverse points

General information

PSAS was described as a major part of Bluebush shrubland (BLUS) in the Murchison River catchment (Curry et al. 1994) and then first described as a distinct habitat in the north-eastern Goldfields survey (Pringle et al. 1994) and later in the Sandstone, Yalgoo and Paynes Find area survey (Payne et al. 1998b). It is characterised by the dominance of *Maireana pyramidata* (sago bush), which also becomes dominant in other chenopod habitat types altered by grazing. Bladder saltbush low shrubland (BLSS, #72) and Plain mixed halophyte shrubland (PXHS, #70) are habitat types that may become dominated by *M. pyramidata* as condition declines. Discriminating between natural *M. pyramidata*-dominated communities and grazing states is complicated and requires local appreciation of patterns of plant zonation and topography. Natural *M. pyramidata* associations are typically found on surfaces with less sand content than BLSS and PXHS in lake country, and are not naturally dominant in drainage tracts carrying concentrated flow.

PSAS occurs on near-level alluvial plains with Red loamy earth, shallow loam, cracking or non-cracking clay soils. Many sites and soils described were identified as degraded or having features that suggested past degradation, such as buried horizons and recent deposits. It is generally found upslope of PXHS in lake country and on alluvial plains in the narrow valley floors in upland areas of granitoid- and greenstone-dominated landscapes. PSAS occurs throughout the survey.

Physiognomy and composition of vegetation

PSAS usually occurs as very scattered to moderately close (5–30% PFC) low shrubland, occasionally with a poorly developed mid or tall shrub stratum.

The dominant and common species by strata:

Trees:	Dominant – rarely present other than as emergents; occasionally *Casuarina pauper*
Tall shrubs:	Dominant – rarely present as a recognisable stratum Common – *Acacia tetragonophylla* Others – *Eremophila alternifolia*, *Hakea preissii* (KI), *Pittosporum angustifolium*
Mid shrubs:	Dominant – *Maireana pyramidata* Common – *Atriplex nummularia* subsp. *spathulata*, *Cratystylis subspinescens* (KD) Others – *Eremophila scoparia*, *Hakea preissii* (KI), *Senna artemisioides* subsp. *filifolia* (KI)
Low shrubs:	Dominant – *Maireana pyramidata*, *M. sedifolia*, *M. triptera* Common – *Atriplex vesicaria* (KD), *Chenopodium curvispicatum* (KD), *Enchylaena tomentosa* (KD), *Maireana tomentosa*, *Ptilotus obovatus*, *Rhagodia drummondii* (KD), *Solanum lasiophyllum* Others – *Atriplex bunburyana* (KD), *A. stipitata*, *Frankenia* spp., *Lycium australe*, *Maireana georgei* (KD), *Solanum orbiculatum*, *Tecticornia doliiformis*
Other plant forms:	Common – *Sclerolaena diacantha* (perennial herb) Other – *Sida spodochroma* (perennial herb)

Priority flora

Austrostipa burgesiana (Priority 1) was recorded near one site.

Ecological disturbance

Fenceline effects indicate that PSAS is preferentially grazed. While *Maireana pyramidata* is notably resistant to grazing (Mitchell and Wilcox 1994), grazing impacts are more noticeable in the diversity and abundance of smaller perennial shrubs. The species most likely to decrease in response to grazing include *Atriplex* spp., *Enchylaena tomentosa* (ruby saltbush) and *Maireana georgei* (George's bluebush), perhaps to be replaced by *M. triptera* (three-winged bluebush), *Ptilotus obovatus* (cotton bush) and *Solanum lasiophyllum* (flannel bush), particularly in consecutive favourable seasons. A conspicuous increase in *Hakea preissii* (needle bush) and *Solanum orbiculatum* (wild tomato) is a reliable indicator of previous overgrazing.

The general lack of slope and diffuse nature of surface run-on provides some soil stability, which is assisted by cryptogamic crusting when present. However, overgrazing of this habitat often results in soil structural degradation, which can increase localised sheet flow and result in localised erosion and/or deposition. In the greenstone-dominated areas, earth dams tend to be located in the broad drainage floors that support this habitat which is then frequently affected by grazing. In these areas, plant species composition and cover decrease through the removal of palatable species. In some instances, the overuse of this habitat has led to scald expansion across the soil surface and gully formation, especially near dams and where vehicle tracks on gradients have caused local incision and concentration of sheetwash. The breakdown of bush mounds is also a major loss of recruitment niches.

Concentration of water along a fenceline has caused gully erosion through an alluvial plain supporting *Maireana pyramidata* (sago bush) shrubland

Gradational associations

PSAS often transitions downslope into PXHS and BLSS in lake country and upslope into Calcareous pearl bluebush shrubland (CPBS, #31) in upland areas, particularly in the greenstone-dominated areas. Observations of fenceline effects reveal that PSAS may expand laterally into more concentrated drainage systems naturally supporting *Atriplex*-dominated communities. This expansion is usually driven by grazing disturbance in saltbush populations reducing interspecies competition.

Land systems

PSAS is the major habitat type in the Carnegie, Bunyip, Gundockerta, Lefroy and Moorebar land systems and a minor habitat type in the Dundas, Kanowna, Kurrawang and Woolibar land systems.

Maireana pyramidata (sago bush) shrubland on a Hard cracking clay soil on a gilgai plain in the Bunyip land system

Uncommon habitats in the Depositional plain mixed halophyte shrubland habitat group

74 Frankenia low shrublands (FRAN)

Sampling

FRAN was not sampled during this survey but it was present and observed at 4 traverse points

General information

FRAN was described as a type of Mixed halophytic shrubland in the Murchison River catchment survey (Curry et al. 1994) and as a distinct habitat in the north-eastern Goldfields (Pringle et al. 1994) and Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b) surveys. FRAN occurs in saline alluvial tracts near salt lakes and in landscapes with saline duplex and clay soils. The ability to take up salt and then exude it through leaf pores enables *Frankenia* species to tolerate levels of salinity beyond the range of many other halophytic shrubs. FRAN communities are typified by other salt-exuding taxa, most noticeably *Gunniopsis* species. The harshness of the environment in which *Frankenia* species tend to dominate is characteristically less diverse than the mixed halophyte associations usually found upslope, such as Plain mixed halophyte shrubland (PXHS, #70).

Physiognomy and composition

FRAN consists of very scattered to scattered (5–15% PFC) low shrubs and occasional mid shrubs. Trees, tall shrubs and perennial grasses are rare. *Frankenia* species invariably dominate the low shrub stratum. Other common perennial low shrubs include *Atriplex vesicaria* (bladder saltbush, KD), *Cratystylis subspinescens* (Australian sage, KD), *Gunniopsis quadrifida* (sweet samphire), *Lycium australe* (Australian boxthorn), *Maireana pyramidata* (sago bush), *M. tomentosa* (felty bluebush) and *Tecticornia* species (samphire).

Ecological disturbance

Frankenia species are less palatable to livestock than some other plants with which they are associated. In grazed scenarios, *Frankenia* species may increase in abundance through the demise of palatable species such as *Atriplex vesicaria, Cratystylis subspinescens* and *Gunniopsis quadrifida*. Hence, a relative increase in *Frankenia* species with a loss of other species may indicate excessive grazing pressure. Thus, it is important to discriminate between natural, highly saline areas dominated by *Frankenia* species and habitat types further upslope in which *Frankenia* has invaded, taking up niches vacated by plants removed through grazing. The high salinity of FRAN communities provides some resistance to grazing and they are only likely to be substantially altered when close to fresh water sources.

Gradational associations

FRAN frequently occupies a zone between samphires downslope in Samphire shrubland (SAMP, #71) and *Atriplex* and *Maireana* associations – Bladder saltbush low shrubland (BLSS, #72) and Plain mixed halophytic shrubland (PXHS, #70) – on higher, better drained soils in lake country. Overlap between these communities is considerable, and *Frankenia* species frequently dominate patches well into the *Atriplex* and *Maireana* communities, reflecting a mosaic of subtle differences in soil characteristics.

Land systems

FRAN is a minor habitat type in the Carnegie, Lefroy, Rowles and Yardina land systems.

75 Sugarwood, mixed chenopod shrubland (SWCS)

Sampling

2 inventory sites, 3 traverse points

General information

SWCS was first described in the WA Nullarbor survey (Waddell et al. 2010), where it is a common habitat in certain locations in the south-west. In the southern Goldfields, it is uncommon and restricted to the south-east. It is typically found in closed depressions within calcrete plains overlain by calcareous loams. Soils are Calcareous loamy earth or Calcareous gravelly loamy earth.

Physiognomy and composition of vegetation

SWCS consists of a scattered (>10–20% PFC) tall shrubland over a scattered to moderately close (>10–30% PFC) mid or low shrubland. The tree and/or tall shrub stratum is dominated by *Myoporum platycarpum* (sugarwood). *Eucalyptus gracilis* (white mallee) is common. The mid and low shrub strata are dominated by *Cratystylis conocephala* (false bluebush) and/or *Maireana sedifolia* (pearl bluebush). Other common flora include mid and low shrubs: *Atriplex nummularia* subsp. *spathulata* (old man saltbush), *A. vesicaria* (bladder saltbush), *Eremophila decipiens* (slender fuchsia), *E. deserti*, *Lycium australe* (Australian boxthorn), *Olearia calcarea*, *Ptilotus obovatus* (cotton bush) and *Senna artemisioides* subsp. *filifolia* (desert cassia).

Ecological disturbance

The release of the Rabbit Calicivirus in the late 1990s and its impact in reducing rabbit numbers has resulted in an increase in recruitment of *Myoporum platycarpum* and *Acacia papyrocarpa* (western myall) across the Nullarbor and adjacent western regions. Dense stands are now common in these areas, though a natural decrease in some populations of *M. platycarpum* is occurring in some localities following consecutive, extended dry seasons.

Gradational associations

SWCS often occurs as a transitional habitat type between Eucalypt, false bluebush woodland (EFBW, #53) and Plain mixed halophyte shrubland (PXHS, #70), where level to very gently undulating calcareous plains with Calcareous shallow loam soils transition into clay depressions. Where the soil surface becomes sandier SWCS transitions into Mallee, hummock grass (spinifex) woodland (MHGW, #35).

Land systems

SWCS is a minor habitat type in the Woorlba land system. It is also infrequently observed in the Dundas, Gundockerta, Harms, Woolibar, Yandamurrina and Yardilla land systems in the east of the survey, becoming more frequent towards the Nyanga Zone in the Nullarbor Province.

Myoporum platycarpum (sugarwood) among a mixed chenopod understorey on a Calcareous loamy earth soil in the Dundas land system

76 Atriplex low shrubland (ATLS)

Sampling

4 inventory sites, 5 traverse points

General information

ATLS is described for the first time. It occurs in closed depressions near Fraser Range, as well as on the lower slopes of rises, in the south-east of the survey area. ATLS is considered a distinct habitat, despite being botanically similar to other WA rangeland *Atriplex*-dominated habitat types, because of its landscape setting. The soils on rises are Calcareous shallow loam or Calcareous loamy earth. A mantle of coarse calcrete gravel may be present, as well as gabbro or gneiss bedrock outcrop associated with the Albany-Fraser Orogen. Closer to drainage foci, soils become heavier-textured Calcareous clay loam, Shallow cracking clay and Self-mulching cracking clay.

Physiognomy and composition of vegetation

ATLS consists of a scattered to moderately close (>10–25% PFC) low shrubland dominated by *Atriplex* species. *A. vesicaria* (bladder saltbush; KD) typically dominates, though *A. bunburyana* (silver saltbush; KD) and *A. stipitata* (kidney saltbush; KI) may also be present. Other strata are poorly developed, but isolated individuals of *Cratystylis conocephala* (false bluebush), *Dodonaea viscosa* subsp. *angustissima*, *Eremophila decipiens* (slender fuchsia), *Myoporum platycarpum* (sugarwood), and *Solanum orbiculatum* (wild tomato) are often present.

Ecological disturbance

Atriplex bunburyana and *A. vesicaria* are highly palatable to livestock. In some degraded areas, these saltbushes are replaced by the unpalatable *A. stipitata*, which can also dominate some ungrazed habitats so it is not definitive evidence of a grazing-induced succession. In some areas *Dodonaea viscosa* subsp. *angustissima* forms thickets from which many younger plants radiate out from. The increase in the abundance of *D. viscosa* subsp. *angustissima* may be in response to the Rabbit Calicivirus reducing the rabbit population and allowing recruitment.

Atriplex low shrubland with scrub encroachment by *Dodonaea viscosa* subsp. *angustissima* in a closed depression in the Symons land system

ATLS, like other saltbush-dominated communities, is vulnerable to fire (Fitzgerald 1976; Graetz and Wilson 1984). Since regeneration is by seed alone, if grazing pressure inhibits recovery after fire, there is risk of eliminating the seed bank (Hodgkinson and Griffin 1982). *Atriplex* species are also susceptible to moisture stress and will shed their leaves. Immediately after significant rainfall following drought or fire events, remaining saltbushes need protection from grazing to allow mature plants to recover vigour and set seed. In many instances across the southern rangelands this has not happened (Waddell et al. 2010) and now ATLS, like other

Atriplex-dominated habitat types, can be seen in various states of transition to Speargrass and wallaby grass open grassland (SWOG, #77) or Annual herbland (ANNH, #78), which are considered degraded post-transition vegetation states.

Gradational associations

ATLS is one of the components making up the mosaic of habitat types around the hills and rises associated with Fraser Range. Some gradations may be an effect of disturbance induced by grazing, fire or a combination of both, with ATLS in various transition states between SWOG or ANNH.

Where soils become deeper, lighter-textured and *Eucalyptus oleosa* subsp. *oleosa* (giant mallee) becomes more abundant, ATLS transitions into *Eucalyptus oleosa*, saltbush woodland (EOSW, #56) or Eucalypt, false bluebush woodland (EFBW, #53), where *Cratystylis conocephala* (false bluebush) is the more dominant understorey shrub.

Land systems

ATLS is a minor habitat type in the Gnamma, Symons and Yandamurrina land systems in the south-east of the survey.

K Depositional plain grassland habitats

This group of habitat types was first described in the WA Nullarbor survey (Waddell et al. 2010) where they occur on the calcrete and limestone plains of the Nullarbor. Similar habitat types were identified around Fraser Range in the east of the southern Goldfields. They are considered to be predominantly altered vegetation associations in an irreversible state of transition. These habitat types once supported a low shrub stratum which has since been removed through the combined effects of an increased fire frequency and overgrazing, initially by rabbits and later compounded by livestock. The loss of perennial shrubs and replacement by open grassland has increased the susceptibility of these habitats to wildfires. These altered vegetation associations are unlikely to support a low shrub stratum of palatable perennial shrubs in the future. They now support open grassland and/or herbland with sparse shrubs. Some low-lying areas, such as valley floors, claypans and drainage foci, may have originally supported variations of these seasonally dependent vegetation associations, but with a more diverse suite of palatable perennial shrubs and grasses than what is now supported by these areas. In favourable seasons, these habitats now support dense stands of short-lived and annual grasses and herbs. In dry periods, they are susceptible to wind erosion because of the scarcity of perennial plants.

77 Speargrass and Wallaby grass open grassland (SWOG)

Sampling

3 inventory sites, 31 traverse points

General information

SWOG was first described in the WA Nullarbor survey (Waddell et al. 2010). It is a major habitat type throughout the Nullarbor region, common on limestone plains and in closed depressions within calcrete plains. In the southern Goldfields, SWOG is restricted to the east around the hills associated with Fraser Range on lower footslopes, pediments, valley floors and closed depressions. Soils are Red shallow loam and Very shallow soil over calcrete on the slopes and pediments, and Calcareous shallow loam, Shallow cracking clay or Hard cracking clay in the valley floors and depressions. In the Nullarbor, SWOG consists of open tussock grassland dominated by *Austrostipa scabra* (speargrass), generally with *Rytidosperma caespitosum* (wallaby grass) common, whereas in the Fraser Range area, SWOG is dominated by *R. caespitosum*, with *A. scabra* less dominant but still common.

It is considered a fire-induced vegetation association, though overgrazing may also initiate transition. Patches of SWOG are likely to have always existed in a mosaic state and transition pattern between chenopod low shrublands. The vegetation has become irreversibly altered because of increased fire frequency and grazing by rabbits and livestock. In the southern Goldfields, this scenario is similar to SWOG in the Nullarbor where it now dominates extensive areas, having replaced other habitat types by increasing the fire susceptibility of the areas it occurs within.

Physiognomy and composition of vegetation

SWOG consists of open tussock grassland dominated by *Rytidosperma caespitosum* with *Austrostipa scabra*. Other perennials, when present, typically only occur as isolated individuals.

The dominant and common species by strata:

Trees:	Dominant – rarely present other than as emergents Occasional – *Myoporum platycarpum*
Tall shrubs:	Dominant – rarely present other than as emergents Occasional – *Acacia burkittii*, *A. hemiteles*, *Dodonaea viscosa* subsp. *angustissima*, *Myoporum platycarpum*
Mid shrubs:	Dominant – not present as a recognisable stratum Occasional – *Atriplex nummularia* subsp. *spathulata*, *Cratystylis conocephala*, *Pimelea microcephala*, *Scaevola spinescens*
Low shrubs:	Dominant – not present as a recognisable stratum Common – *Atriplex stipitata*, *A. vesicaria*, *Maireana sedifolia* Occasional – *Chenopodium curvispicatum*, *Enchylaena tomentosa*, *Ptilotus obovatus*, *Scaevola spinescens*, *Solanum lasiophyllum*
Perennial grasses:	Dominant – *Rytidosperma caespitosum* Common – *Austrostipa scabra* Others – *Enneapogon avenaceous*, *E. intermedius*, *Eragrostis dielsii*, *E. setifolia*
Other plant forms:	Common – *Asphodelus fistulosus* (perennial herb; KI) Others – *Carrichtera annua* (perennial herb; KI), *Salvia verbenaca* (perennial herb; KI)

Ecological disturbance

Some areas of SWOG may represent an altered vegetation state caused by overgrazing and/or increased fire frequency. In favourable seasons, SWOG is highly productive and during the active growth phase is readily grazed. *Rytidosperma caespitosum* is palatable and is preferentially sought after by herbivores. If total grazing pressure is not effectively managed, especially during extended dry periods, wallaby grass can be eliminated and SWOG can become dominated by only speargrass and unpalatable annual species, inducing another vegetative transition into an Annual herbland (ANNH, #78), and reducing the long-term carrying capacity of the grassland.

Degraded SWOG or ANNH habitat types can also be colonised by perennial herbs such as *Asphodelus fistulosus* (onion weed) and to a lesser extent *Salvia verbenaca* (wild sage), particularly if there is soil disturbance. These 2 unpalatable species compete strongly with palatable species and have successfully invaded overgrazed areas, significantly reducing the productivity of the habitats.

Asphodelus fistulosus poses a significant threat to the composition of SWOG habitats. Infestations can become so dense that grasses are suppressed and eventually outcompeted. Although *A. fistulosus* prefers sandy alkaline soils, through its ability to readily colonise disturbed sites, it is becoming well established along roadsides and railway lines, facilitating its spread into a range of other habitat types. Considered primarily a weed of disturbed locations, the threat it poses to undisturbed habitats has been underestimated by some observers. It is now common and naturalised throughout southern parts of South Australia and western WA, with scattered populations also in Queensland, Tasmania and southern Northern Territory. Being well adapted to arid conditions, *A. fistulosus* requires priority attention to develop an understanding of its ecology to provide strategies for management.

Gradational association

Within valley floors, SWOG is often extensive and grades into Atriplex low shrubland (ATLS, #76), Calcareous pearl bluebush shrubland (CPBS, #31), or Stony dodonaea low shrubland (SDLS, #23) on adjacent pediments and rises. Along ecotone boundaries bordering valley floors, where mallees become prominent, SWOG often merges with Ridge crest eucalypt woodland (RCEW, #24) on calcrete ridges, or Eucalypt, false bluebush woodland (EFBW, #53) along the plains. When degraded, SWOG transitions into or is replaced by ANNH.

Land systems

SWOG is a major habitat type in the Symons land system and a minor habitat type in the Gnamma, Nyanga and Woorlba land systems.

Speargrass and wallaby grass open grassland on a Red shallow loam soil on an undulating pediplain in the Symons land system

78 Annual herbland (ANNH)

Sampling

1 inventory site, 12 traverse points

General information

ANNH was first described in the WA Nullarbor survey (Waddell et al. 2010) in areas receiving local drainage, such as closed depressions and claypans. In the southern Goldfields, ANNH is uncommon, occurring on valley floors and closed depressions at the base of footslopes associated with the hills of Fraser Range in the east. Soils are likely to mostly consist of Alkaline red shallow loamy duplex, Shallow cracking clay and Hard cracking clay, with minor Calcareous shallow loam (underlain by calcrete) on low rises at the margins of depressions.

Physiognomy and composition of vegetation

ANNH occurs as a very scattered to scattered (>2.5–15% PFC) herbland of perennial and annual herbs and grasses. No specific species dominate the tree, tall shrub or low shrub strata, though occasional perennial trees and shrubs – such as *Myoporum platycarpum* (sugarwood), *Dodonaea adenophora, Enchylaena tomentosa* (ruby saltbush) and *Ptilotus obovatus* (cotton bush) – were infrequently observed as isolated individuals.

Ecological disturbance

ANNH is considered a severely degraded, post-transition vegetation state of Atriplex low shrubland (ATLS, #76) and Speargrass and wallaby grass open grassland (SWOG, #77). Where ANNH is stable and not actively eroding it may contain an extensive cryptogamic crust and abundant palatable perennial herbs – such as *Eriochiton sclerolaenoides* (woolly bindii), *Maireana trichoptera* (pink-seeded bluebush), *Sclerolaena diacantha* (grey bindii) – and perennial grasses, such as *Rytidosperma caespitosum* (wallaby grass) and *Enneapogon* spp. In overgrazed areas and where the cryptogamic crust is disturbed or absent, palatable species are replaced by *Atriplex acutibractea* (toothed saltbush), *Carrichtera annua* (Ward's weed), *Euphorbia drummondii* (balsam), *Mesembryanthemum crystallinum* (ice plant), *Rhodanthe floribunda* and *Roepera iodocarpa* (violet twinleaf), *Salsola australis* (roly poly) and *Sclerolaena patenticuspis* (spear-fruit copperburr). Where there is soil disturbance, these areas can become invaded by the perennial herbs *Asphodelus fistulosus* (onion weed) and *Salvia verbenaca* (wild sage). In dry periods, areas are highly susceptible to wind erosion because the annual and short-lived shrub components disappear and leave the ground surface exposed.

Gradational associations

ANNH is commonly found in low-lying areas, such as claypans, grading up onto the marginal slopes of the surrounding plains and pediments which support low shrubland such as Calcareous pearl bluebush shrubland (CPBS, #31), ATLS or SWOG.

Land systems

ANNH is a minor habitat type in the Gnamma, Symons and Wyralinu land systems.

Annual herbland on an Alkaline red shallow loamy duplex soil at the base of a footslope in the Wyralinu land system

L Calcrete or kopi associated woodland or shrubland habitats

These habitat types are generally confined to salt lake systems and adjacent drainage tracts. They form where either groundwater has precipitated calcium carbonate to form calcrete platforms and gently undulating plains, or where gypsiferous sediments have blown off playas and lake beds to become stabilised as kopi dunes around lake margins. They support a distinctive range of species, with *Casuarina pauper* (black oak) common.

The habitat types in this group include Kopi dune woodland (KOPI, #79), Calcareous casuarina, acacia shrubland or woodland (CCAS, #80) and Calcareous casuarina, *Cratystylis* woodland (CCCW, #81). Similar to the latter 2 is Calcareous pearl bluebush shrubland (CPBS, #31), which occurs on calcareous plains in broad, sluggish drainage tracts and on soils developed largely in situ on greenstones. However, in recognition of its chenopod-dominated composition, CPBS is described in the stony plain and low rise chenopod shrubland group (Habitat type group C).

79 Kopi dune woodland (KOPI)

Sampling

4 inventory sites, 3 traverse points

General information

KOPI was described in the north-eastern Goldfields (Pringle et al. 1994), Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b) and the WA Nullarbor (Waddell et al. 2010) surveys. These variable communities occur as dunes and undulating banks of windblown gypsiferous sediments on and adjacent to salt lake beds, fringing Ponton Creek and adjacent occluded salt pans among the sand dunes in the Great Victoria Desert. Kopi dunes form by prevailing winds deflating dry, bare lake beds and building up powdery dunes of microcrystalline gypsum around lake and pan margins. Soils are Calcareous sandy earth and gypsiferous, though they are considered recent deposits.

Physiognomy and composition of vegetation

Vegetation communities growing on kopi dunes are diverse. Low trees are generally dominant, followed by the low shrub stratum. The mid to tall shrub strata is variable but is typically very scattered (>2.5–5% PFC). In the north, the tree stratum is often occupied by *Casuarina pauper* (black oak), while in the south eucalypts are more common. Despite kopi dunes being geomorphically similar, eucalypts vary according to regional distribution. The understorey usually consists of very scattered to scattered (5–20% PFC) halophytes, such as *Atriplex vesicaria* (bladder saltbush) and species of *Frankenia* and *Tecticornia* (samphire).

Kopi dune supporting a mixed woodland on the east of an occluded playa in the Yardina land system

The dominant and common species by strata:

Trees:	Dominant – variable; often *Casuarina pauper* Common – variable; *Callitris columellaris*, *Myoporum platycarpum*
Mallees:	Common – variable; *Eucalyptus horistes*, *E. oleosa* subsp. *oleosa*, *E. rigidula*
Tall shrubs:	Dominant – rarely present as a recognisable stratum Common – *Dodonaea viscosa*, *Melaleuca lanceolata* Other – *Santalum acuminatum*
Mid shrubs:	Dominant – rarely present as a recognisable stratum Common – *Cratystylis conocephala, Eremophila decipiens*, *E. deserti* Other – *Acacia hemiteles*
Low shrubs:	Dominant – various *Tecticornia* spp. Common – *Atriplex vesicaria* (KD), *Frankenia* spp., *Maireana erioclada*, *M. pentatropis*, *Rhagodia crassifolia* (KD), *R. drummondii* (KD), *Roepera aurantiaca*

Ecological disturbance

Grazing impact will be determined by the quality of nearby water sources. If the water is fresh, continuous heavy grazing may result and the palatable shrubs *Atriplex vesicaria* and *Rhagodia* spp. could decrease. However, because of the variable nature of kopi dunes, the absence of these species from an area may also be natural and not a result of grazing.

Gradational association

The gypsiferous sediments are quite different from adjacent alluvial plains soils and hence the vegetation boundaries are well-defined, though there may be mutually inclusive low shrubs – such as *Atriplex vesicaria* and species of *Frankenia* and *Tecticornia* – from adjacent habitat types.

Land systems

KOPI is a minor habitat type in the Carnegie, Lake Deborah, Lefroy, Ponton and Yardina land systems.

80 Calcareous casuarina, acacia shrubland or woodland (CCAS)

Sampling

11 inventory sites, 92 traverse points

General information

CCAS was described in the north-eastern Goldfields survey (Pringle et al. 1994) where it was a major habitat type in the south. It was also briefly described in the Sandstone, Yalgoo and Paynes Find area survey (Payne et al.1998a) where it is largely restricted to the far south-east. It typically occurs adjacent to salt lakes on level to very gently undulating plains over calcrete, rather than on discrete calcrete platforms. Soils are Very shallow soil over calcrete, Calcareous gravelly shallow loam, Red–brown hardpan shallow loam or Red sandy earth, often over calcrete, and occasionally with a sparse mantle of calcrete rubble. CCAS also occurs infrequently on Red shallow sand or Red shallow loam when associated with granitic low rises in sandplains.

Physiognomy and composition of vegetation

CCAS occurs as a scattered to moderately close (15–30% PFC) *Casuarina pauper* (black oak) woodland with a prominent acacia tall shrub stratum. Less frequently, it occurs as a tall to mid acacia shrubland with a sparse casuarina tree stratum.

The dominant and common species by strata:

Trees:	Dominant – *Casuarina pauper* Other – *Acacia aneura* (in the north)
Tall shrubs:	Dominant – *Acacia aneura* (in the north), *A. burkittii, A. ramulosa* var. *ramulosa* Common – *Acacia ramulosa* (in sandplains), *A. tetragonophylla*, *Alyxia buxifolia*, *Exocarpos aphyllus* Others – *Acacia hemiteles* (KI), *Dodonaea viscosa* subsp. *angustissima*, *Eremophila alternifolia*, *Santalum spicatum*
Mid shrubs:	Dominant – *Acacia hemiteles* (KI) Common – *Dodonaea lobulata* (KI), *Eremophila decipiens*, *Senna artemisioides* subsp. *filifolia* (KI) Other – *Eremophila scoparia*
Low shrubs:	Dominant – *Ptilotus obovatus*, *Scaevola spinescens* (KD) Common – *Enchylaena tomentosa* (KD), *Maireana georgei* (KD), *M. triptera*, *Olearia muelleri*, *O. pimeleoides*, *Rhagodia drummondii* (KD), *Solanum lasiophyllum* Others – *Atriplex bunburyana* (KD), *A. vesicaria* (KD), *Maireana sedifolia*
Perennial grasses:	Dominant – not present as a recognisable stratum Others – *Austrostipa elegantissima*, *A. scabra*
Other plant forms:	Common – *Leichhardtia australis* (climber)

Ecological disturbance

Pringle et al. (1994) found that a mix of the following palatable species would be expected in CCAS when it is in good condition: *Atriplex bunburyana* (silver saltbush), *A. vesicaria* (bladder saltbush), *Enchylaena tomentosa* (ruby saltbush), *Maireana georgei* (George's bluebush), *M. sedifolia* (pearl bluebush), *Ptilotus obovatus* (cotton bush), *Rhagodia drummondii* (lake-fringe rhagodia) and *Scaevola spinescens* (currant bush). In the southern Goldfields, tussocks of *Austrostipa elegantissima* (feather speargrass) indicate very good condition when accompanied by a mix of these species. Species – such as *Acacia hemiteles* (tan wattle), *Dodonaea lobulata* (bead hopbush), *Eremophila scoparia* (broom bush) and *Senna artemisioides* subsp. *filifolia* (desert cassia) – frequently dominate low and mid shrub strata in heavily grazed or historically burnt areas. Their prominence in unburnt understoreys represents a decline in habitat condition.

Gradational associations

CCAS transitions into Calcareous pearl bluebush shrubland (CPBS, #31) as *Casuarina pauper* (black oak) and acacias become less prominent in the overstorey and chenopods become more conspicuous in the understorey. As the soil becomes deeper and sandier, CCAS may transition into Lakeside sandy bank casuarina shrubland (LSCS, #67) when adjacent to lake country, or into Plain eucalypt (mallee), acacia woodland (PEAW, #43) when away from lake country and *C. pauper* is replaced by mallees.

Land systems

CCAS is the dominant habitat type in Deadman land system and a minor habitat type in Bunyip, Carnegie, Cundeelee, Cundlegum, Gundockerta, Helag, Kirgella and Lefroy land systems.

Casuarina pauper (black oak) woodland over a tall shrubland of *Acacia burkittii* (sandhill wattle) and *A. ramulosa* (horse mulga) on a Red–brown hardpan shallow loam soil in the Deadman land system

Uncommon habitat in the Calcrete or kopi associated woodland or shrubland habitat group

81 Calcareous casuarina, *Cratystylis* woodland (CCCW)

Sampling

1 inventory site

General information

CCCW is described for the first time. It is similar to Calcareous casuarina, acacia shrubland or woodland (CCAS, #80) in topographic location, soil type and the dominant tree (*Casuarina pauper*), but differs because *Cratystylis conocephala* (false bluebush) is prominent in the mid and low shrub strata. CCCW was only seen in the east of the survey area near Harris Lake, north-east of Fraser Range. It occurs on level plains adjacent to playas. Soil is Calcareous loamy earth.

Physiognomy and composition of vegetation

CCCW is a moderately close (>20–30% PFC), low (<8 m) *Casuarina pauper* (black oak) woodland over a prominent but scattered (15–20% PFC) mid and low shrubland dominated by *Cratystylis conocephala*. The tall shrub stratum is poorly developed, with only isolated individuals of *Acacia hemiteles* (tan wattle), *Alectryon oleifolius* (bullock bush), *Dodonaea lobulata* (bead hopbush) and *Eremophila decipiens* (slender fuchsia). *Enchylaena tomentosa* (ruby saltbush), *Maireana tomentosa* (felty bluebush) and *Rhagodia drummondii* (lake-fringe rhagodia) are common but rarely present beyond the shelter of tree-based clumps. Perennial grasses are absent. In adjacent drainage tracts and lake margins, *Cratystylis subspinescens* (Australian sage) and *Maireana pyramidata* (sago bush) become more common in the understorey.

Gradational associations

CCCW is a distinctive habitat type that has clearly defined boundaries where it abuts sand sheets supporting Mallee, hummock grass (spinifex) woodland (MHGW, #35). Proximal to lake margins, *Cratystylis subspinescens* becomes increasingly prominent in the understorey until CCCW gives way to a sage-dominated low shrubland.

Land systems

CCCW is a minor habitat type in the Yardina land system.

M Drainage focus habitats

This group of habitat types usually occurs on localised drainage foci in the lower lying parts of the landscape. Occasionally, habitat types occur on seep zones or within closed depressions in some upland landscapes. These habitat types are distinctive and often support unique vegetation associations such as Drainage focus eucalypt woodland (DFEW, #82), Melaleuca swamp shrubland (MESS, #84), Swamp eucalypt woodland (SWEW, #83) and Lignum swamp (LISW, #85). Drainage foci are often microhabitats within more extensive habitat types, and as such are uncommon, making up a very small proportion of the survey area. However, as microhabitats within a semi-arid environment, these foci may have particular value as ecological refuges important for maintaining regional connectivity and sustaining ecosystem processes and functions (Morton and Stafford Smith 1994; Davis et al. 2013), particularly in consideration of a drying climate.

82 Drainage focus eucalypt woodland (DFEW)

Subtype: Drainage focus *Eucalyptus salubris* woodland (DFEW–S)

Subtype: Drainage focus *Eucalyptus urna* woodland (DFEW–U)

Subtype: Drainage focus *Eucalyptus diptera* woodland (DFEW–D)

Subtype: Drainage focus *Eucalyptus terebra* woodland (DFEW–T)

Sampling

DFEW: 9 inventory sites, 7 traverse points

DFEW–S: 7 inventory sites, 10 traverse points

DFEW–U: 3 inventory sites

General information

DFEW is described for the first time. DFEW is broad habitat type found throughout the survey area in a variety of situations and floristic associations. Consequently, it has a variety of associated soil types. Eucalypt communities associated with drainage foci show much variability and usually consist of a species-specific association connected with a drainage focus (gilgai, seep line, closed depression) within the matrix of a more extensive eucalypt woodland habitat. The varied landscape positions of the drainage foci are: closed depressions within levels plains; around gilgais; and along seep zones on the lower slopes and bases of rises and footslopes, particularly where they are associated with fault structures, geological contacts and pediments.

DFEW was treated as the generalised habitat type where different eucalypt species were dominant, and the subtypes were used to record species-specific information in the field. The 2 most frequently observed eucalypts dominating the tree stratum were *E. salubris* (gimlet; DFEW–S), and *E. urna* (DFEW–U). Members of the Contortae series (gimlets) were also used to provide subdivision for specific areas. The presence of *E. diptera* (two-winged gimlet), which is locally common to DFEW in the south-west of the survey, characterises DFEW–D; and *E. terebra* (Balladonia gimlet), which is locally common to DFEW in the south-east, characterises DFEW–T.

Soils of DFEW and its subtypes vary according to topography. Within plains supporting extensive eucalypt woodland, the soils in drainage depressions are often Calcareous loamy earth, Red shallow loam (often with calcareous concretions) or Alkaline red or yellow–brown shallow loamy duplexes. Around gilgais, which are often associated with mafic intrusions, the soils are typically Self-mulching cracking clay and, less commonly, Hard cracking clay. These areas may have irregular surfaces due to gilgai microrelief and minor crabholes, with a mantle of mafic or metasedimentary stones of variable density and size brought to the surface by shrink and swell clays. DFEW–S is regularly associated with these locations, though DFEW with *E. griffithsii* (Griffith's grey gum) is also common in gilgais associated with mafic geology. DFEW–S is also commonly associated with sluggish drainage tracts below low, subdued breakaways composed of ferruginous duricrusts. Here the soils are often Red loamy earth. In the south-west of the Youanmi South Zone, drainage foci supporting DFEW–U and DFEW–D tend to occur at the base of gently inclined footslopes and in alluvial valley floors with meandering drainage tracts subject to infrequent flooding. These soils are often Calcareous loamy earth.

Physiognomy and composition of vegetation

DFEW and its subtypes typically occur as a moderately close (>20–30% PFC) eucalypt woodland over a scattered to close (>10–50% PFC) low shrubland frequently dominated by a single species such as *Eremophila clavata*, *E. pustulata* (warted eremophila) or *Templetonia ceracea*. The tree stratum is frequently dominated by *Eucalyptus salubris* (DFEW–S) or *E. urna* (DFEW–U). Development of the understorey tends to be inversely related to upper canopy coverage – when the upper canopy is open, the understorey is frequently well developed and vice versa when the upper canopy is denser. The tall and mid shrub strata are usually poorly developed, with isolated individuals of *Acacia nyssophylla*, *Eremophila* species, *Olearia muelleri* (Goldfields daisy), *Santalum acuminatum* (quandong) and *Senna artemisioides* subsp. *filifolia* (desert cassia). Perennial grasses are sparse.

Where gilgai occur, the vegetation frequently consists of very scattered to scattered (>2.5–20% PFC) *E. salubris* surrounding a variably dense (20–50% PFC), tall to low shrub stratum typically dominated by a single species. Occasionally, *E. griffithsii* is dominant (DFEW), particularly when associated with mafic outcrop. Species from the family Scrophulariaceae frequently form homogenous stands in the mid and low shrub strata: *Eremophila interstans* subsp. *virgata* (KI), *E. maculata*, *E. pustulata*, *E. rugosa* or *E. ternata*. Other shrubs include *Atriplex nummularia* subsp. *spathulata* (old man saltbush), *A. vesicaria* (bladder saltbush, KD), *Enchylaena tomentosa* (ruby saltbush; KD), *Exocarpos aphyllus* (leafless ballart) and *Santalum acuminatum* (quandong), but these are typically scattered and infrequent.

DFEW–D is characterised by the presence of *E. diptera* and consists of a close to closed (>30% PFC) woodland dominated by *E. diptera* or co-dominated by *E. diptera* and *E. urna*. Close thickets of *Melaleuca pauperiflora* subsp. *pauperiflora* frequently dominate the tall shrub stratum. Other *Melaleuca* species and *Santalum acuminatum* are often present but are sparse. Occasional clumps of *Acacia acoma* and scattered *Daviesia aphylla* and *Westringia rigida* (stiff westringia) are common in the low shrub stratum. It occurs in the south-west of the survey.

DFEW–T is characterised by the frequent presence of *E. terebra*. It consists of a moderately close to closed (>20% PFC) woodland variably dominated or co-dominated by a variety of tree and mallee-form eucalypts common to the south-east of the survey: *E. fraseri* subsp. *melanobasis*, *E. laevis*, *E. longissima*, *E. oleosa* subsp. *oleosa* and *E. protensa,* with *E. terebra*. The tall and mid shrub strata are typically sparse with scattered *Dodonaea stenozyga*, *Exocarpos aphyllus*, *Melaleuca* spp. and *Santalum acuminatum*. Species such as *Eremophila ternata*, *Olearia calcarea*, *Scaevola bursariifolia* and *Templetonia rossii* are common in the low shrub stratum and may form homogeneous stands.

Eucalyptus salubris (gimlet) over *Eremophila ternata* on a Hard cracking clay soil in a drainage focus in the Johnston land system

Eucalyptus urna over *Eremophila clavata* on a Red shallow loamy duplex soil in a drainage focus in the Doney land system

Eucalyptus diptera and *E. urna* over *Melaleuca pauperiflora* subsp. *pauperiflora* at the base of footslope on a Calcareous loamy earth soil in a drainage focus in the Forrestania land system

Eucalyptus terebra (Balladonia gimlet) over *Scaevola bursariifolia* and *Templetonia rossii* on a Yellow–brown shallow loam duplex soil in a drainage focus in the Charlina land system

Ecological disturbance

In pastoral areas, some drainage foci have been degraded by animal activity and the Self-mulching clay soil within some gilgais have degraded to cracking clays. The encroachment and dominance of unpalatable shrubs – such as *Eremophila interstans* subsp. *virgata*, which is known to be invasive in these habitats – is likely to be a response to overgrazing. However, the monospecific stands of other species from the family Scrophulariaceae in drainage foci outside the pastoral estate suggest this may not always be in response to grazing pressure or indicate habitat in poor condition.

Outside the pastoral estate not much is known about this habitat type, making it difficult to confidently assess grazing effects. Most plants in DFEW are not particularly palatable or preferred by livestock. However, this feature may also be a legacy of past grazing effects. Herbivores, native and introduced, may have preferentially grazed these areas because the high soil moisture content may have seasonally attracted herbivores to these favourable areas for forage. Regular grazing may have subsequently resulted in the depletion of seed banks and resulted in the eventual elimination of palatable species and the development of monospecific stands of unpalatable species. In low-lying areas, the low relief, dense vegetation and heavy-textured soils, which are intermittently inundated or experience concentrated seepage, suggest DFEW is not particularly susceptible to erosion. However, where seep zones associated with outcrop occur in some upland landscapes, some drainage foci may be vulnerable to disturbances (for example, infrastructure works) with altered natural flow paths leading to problems such as water starvation downslope.

Gradational associations

DFEW and its subtypes may be quite different from the vegetation surrounding the drainage focus and typically has clearly defined boundaries, such as in DFEW habitats associated with gilgai or where the understorey consists of a dense low shrubland dominated by a single species.

In some circumstances, there may be some gradation where drainage foci are in broad alluvial drainage tracts. In the greenstone-dominated landscapes of the Kambalda Zone, DFEW–S is often surrounded by Plain eucalypt, saltbush woodland (PESW, #58). West of the greenstone-dominated landscapes in the Youanmi South Zone, DFEW is typically surrounded by lighter (sandier) textured plains supporting Plain eucalypt, eremophila woodland (PEEW, #59), or it occurs below Colluvial slope eucalypt woodland over non-halophytic shrubland (CEWS, #51). In the south-west, drainage foci supporting DFEW–U and DFEW–D are often surrounded by Sand sheet mallee heath (SAMH, #41) on gently undulating yellow sandplains. In the south-east, drainage foci supporting DFEW–T are often surrounded by Eucalypt, false bluebush woodland (EFBW, #53) on gently undulating calcareous loamy plains in the Dundas, Nanambinia, Salmon Gums Mallee zones and lower slopes of the Fraser Range Zone.

Land systems

DFEW and its subtypes are minor habitat types that feature in many land systems in drainage foci and along seep zones on the lower slopes of footslopes and rises, particularly where they are adjacent to or associated with greenstone or ferruginised landforms.

83 Swamp eucalypt woodland (SWEW)

Sampling

4 inventory sites, 16 traverse points

General information

SWEW is described for the first time. It is associated with sluggish drainage tracts and swamps. Soils are variable owing to alluvial influences, but most classify as duplex soils and are alkaline and calcareous at depth. Soils at the margins are Red loamy earth, and calcareous at depth.

Physiognomy and composition of vegetation

SWEW occurs as a moderately close to close (>20–50% PFC) eucalypt woodland over a well-developed tall shrub stratum. The eucalypt overstorey is variable, ranging from scattered to moderately close (15–25% PFC), with *Eucalyptus cylindrocarpa* (woodline mallee), *E. salubris* (gimlet) or *E. yilgarnensis* (yorrell) dominating. The tall shrub stratum is frequently dominated by homogenous stands of *Acacia hemiteles* (tan wattle) or *Callistemon phoeniceus* (lesser bottlebrush) and can range from a scattered tall shrubland to closed thickets (10% to ≥50% PFC). *Acacia burkittii* (sandhill wattle), *A. nyssophylla*, *Dodonaea viscosa* (sticky hopbush) and *Melaleuca* species are regularly present as isolated individuals. The mid and low shrub strata are poorly developed, though *Duma florulenta* (lignum) may occasionally be present as scattered clumps.

Woodland of *Eucalyptus cylindrocarpa* (woodline mallee) and *E. gracilis* (white mallee) over a thicket of *Callistemon phoeniceus* (lesser bottlebrush) and *Acacia* spp. on an Alkaline red shallow loamy duplex soil in a drainage focus in the Doney land system

Ecological disturbance

Not much is known about disturbance in this habitat type. Disturbance events affecting Drainage focus eucalypt woodland (DFEW, #82) may have similar effects on SWEW. The dominance of unpalatable, invasive shrubs, such as *Acacia hemiteles*, may be in response to past overgrazing.

SWEW habitats are important for enhancing regional connectivity. Where associated with sluggish drainage tracts, SWEW and linked habitats are vulnerable to changes in hydrological processes where surface water flows may be disrupted. Potential impacts, such as water starvation and loss of connectivity between drainage tracts and swamps, need to be considered prior to developing any infrastructure in areas connected to SWEW and similar habitats.

Gradational associations

SWEW is a distinctive habitat type which typically has clearly defined boundaries, though gradation may occur with some bordering habitat types. SWEW may transition into Lakeside (sand sheet) eucalypt woodland with shrubs (LSES, #64) where swamps that have formed in occluded lakes are fringed by lunettes. Gradation may also occur along the edges of drainage tracts flowing through plains supporting Plain eucalypt, eremophila woodland (PEEW, #59).

Land systems

SWEW is a major habitat type in the Rowles and Wangine land systems and a minor habitat type in the Cronin and Doney land systems.

84 Melaleuca swamp shrubland (MESS)

Sampling

7 inventory sites, 4 traverse points

General information

MESS was first described in the Sandstone, Yalgoo and Paynes Find area survey (Payne et al. 1998b). It usually occurs as swamps on broad, alluvial plains adjacent to salt lakes and their tributary systems, but may occur anywhere drainage is locally concentrated, particularly if there is an impervious subsoil layer (calcrete) or bedrock is shallow (granite pavements). Swamps are ephemeral and periodically inundated with water. MESS may occur as densely vegetated drainage foci or as fringing vegetation to claypans, into which the vegetation sometimes encroaches. Soils are Alkaline red or yellow–brown deep sandy duplex, and Self-mulching cracking clay in the lowest depressions.

Physiognomy and composition of vegetation

MESS occurs either as moderately close to close (25–50% PFC) monospecific thickets of *Melaleuca* species in swamps and surrounding claypans, or as fringing thickets restricted to the outer margin of the drainage foci. The tall and mid shrub strata are usually well developed and often contain many juvenile melaleuca. Trees, low shrubs and perennial grasses are usually only a minor component.

While MESS communities tend to occur in either of these structural forms, the composition of *Melaleuca* species may vary in different locations. In the Kambalda Zone, MESS habitats are frequently dominated by dense (>30% PFC) thickets of *Melaleuca phoidophylla*. Scattered low shrubs commonly include *Chenopodium nitrariaceum* (nitre goosefoot), *Enchylaena tomentosa* (ruby saltbush), *Maireana pyramidata* (sago bush), *M. triptera* (three-winged bluebush), *Ptilotus obovatus* (cotton bush) and *Rhagodia* spp. *Duma florulenta* (lignum) is regularly present, particularly in swamps where MESS occurs in the fringing-form around dense stands of Lignum swamp (LISW, #85). Other melaleucas dominating monospecific stands in MESS habitats in this zone included *M. eleuterostachya*, *M. hamata* and *M. pauperiflora* subsp. *fastigiata*.

Along the narrow, alluvial, Red sandy earth terraces flanking Ponton Creek in the north-east of the survey, MESS habitats consist of moderately close (25–30% PFC) thickets of *Melaleuca halmaturorum*, with scattered *Eucalyptus cylindrocarpa* (woodline mallee) and *E. horistes* (pointed-bud mallee).

Within the very gently undulating plain of the Buraminya land system in the south of the survey, infrequent, circular swamps in closed depressions support closed (>50% PFC) thickets of *M. acuminata* subsp. *acuminata*, with *E. conglobata* subsp. *conglobata* and *E. incrassata* (ridge-fruited mallee) common on the outer fringe of the thickets.

Acacia diaphana (Priority 1) was recorded at one site.

Ecological disturbance

Little is known about grazing disturbance. In areas where MESS has a chenopod understorey, palatable species – such as *Atriplex* spp., *Enchylaena tomentosa*, *Maireana* spp. and *Rhagodia* spp. – may decrease under heavy grazing pressure. Feral goats are known to browse some *Melaleuca* species and can cause significant damage during dry periods when they may gather in these areas. Where MESS occurs as ephemeral wetlands, these habitats are important for sustaining ecosystem processes and functions, and thus fit into the restricted use unit category of Morton and Stafford Smith (1994). These are areas whose conservation value peaks under certain conditions – in this case, favourable seasons – and may require special management at these times. This may include reducing livestock numbers, restricting human recreation activities and undertaking feral predator control if animals, such as waterbirds, are breeding.

Gradational associations

MESS is a distinctive and well-defined habitat. It may resemble Swamp eucalypt woodland (SWEW, #83) in some drainage foci where there are eucalypt trees and a mix of other species, such as *Acacia hemiteles* (tan wattle) or *Callistemon phoeniceus* (lesser bottlebrush), among melaleuca shrubs. Some MESS transition into Lignum swamp (LISW, #85) which may be in the lower lying sections of the drainage foci.

Land systems

Except for the Rowles land system where it is a major habitat type, variations of MESS occur throughout the survey in areas subject to inundation. It is a common minor habitat type in the Cronin, Doney, Emu, Johnston, Lefroy, Ponton and Wangine land systems. It is also present, but as a very minor habitat type component, in the Buraminya land system.

Uncommon habitats in the Drainage focus habitats group

85 Lignum swamp (LISW)

Sampling

1 inventory site, 1 traverse point

General information

LISW was described as a minor habitat type in the Sandstone, Yalgoo and Paynes Find area (Payne et al. 1998b) and WA Nullarbor (Waddell et al. 2010) surveys. It is characterised by the presence of *Duma florulenta* (lignum). LISW occurs in non-saline drainage foci such as claypans and swamps within paleodrainage systems or closed depressions that are periodically subject to flooding. Soils are Self-mulching cracking clay, and gilgai are prominent.

Physiognomy and composition of vegetation

LISW is dominated by *Duma florulenta* which forms relatively homogenous stands, sometimes exceeding 50% PFC. Species that can cope with temporary inundation, such as *Marsilea hirsuta* (nardoo), are also common. Some areas within drainage foci have gilgai structure. Accompanying *D. florulenta* are species such as *Eragrostis dielsii* (mallee lovegrass), *E. setifolia* (neverfail) and *Lycium australe* (Australian boxthorn) which are distributed according to the microrelief, where they prefer raised areas or foci edges.

Ecological disturbance

Duma florulenta is rarely eaten and has very low forage value. The palatable grasses *Eragrostis dielsii* and *E. setifolia* may decrease under continuous grazing pressure. Of more significance than grazing are changes in regional climate patterns and changes in hydrological processes. As LISW depends on surface water run-off generated by rainfall, any loss of connectivity between drainage tracts and swamps due to disrupted surface water flows may leave it vulnerable to reduced periods of inundation. The consequence of desiccating habitats is that competition from other plants, normally restricted by submersion or waterlogging, may eventually alter the composition and hydrology, with implications for those species dependent on these habitats.

Gradational association

LISW is typically confined to areas subject to episodic inundation and has defined boundaries, except where it is surrounded by Melaleuca swamp shrubland (MESS, #84) and melaleucas may encroach among the lignum. LISW drainage foci are often surrounded by Bladder saltbush low shrubland (BLSS, #72) or Calcareous pearl bluebush shrubland (CPBS, #31) in lake systems and alluvial plains. Plain eucalypt, eremophila woodland (PEEW, #59) or Eucalypt, false bluebush woodland (EFBW, #53) may border foci margins within plains associated with paleodrainage systems.

Land systems

LISW occurs infrequently throughout the southern Goldfields in areas subject to inundation. Though a minor habitat type, it is most commonly found in the Carnegie, Cronin, Emu, Lefroy, Noondoonia, Nyanga and Rowles land systems.

Inundated swamp with an understorey of *Duma florulenta* (lignum) in the Emu land system

86 Plain mixed low shrubland (PXLS)

Sampling

2 inventory sites

General information

PXLS was first described in the WA Nullarbor survey (Waddell et al. 2010), where it is uncommon and occurs infrequently in depressions in the Caiguna land system in the south. In the southern Goldfields, PXLS is restricted to the south-east in closed depressions within calcareous peneplains. Soils are Calcareous loamy earth, often with calcareous gravels, and Red loamy earth with calcareous subsoil.

Physiognomy and composition of vegetation

PXLS consists of moderately close to close (25–50% PFC) mid shrubland dominated by *Eremophila* species and *Cratystylis conocephala* (false bluebush). The mid and low shrub strata are structurally dominant. Larger shrubs and trees are generally only present as isolated individuals or at the margins of depressions where there is typically an abrupt change into the adjacent habitat types. Common shrubs are *Enchylaena tomentosa* (ruby saltbush), *Eremophila decipiens* (slender fuchsia), *E. interstans* subsp. *interstans*, *Exocarpos aphyllus* (leafless ballart), *Geijera linearifolia* (oilbush), *Scaevola spinescens* (currant bush) and *Westringia rigida* (stiff westringia).

Ecological disturbance

This habitat type was insufficiently sampled to obtain detailed quantitative information on disturbance characteristics. Overgrazing is likely to cause a decrease in palatable shrubs, such as *Enchylaena tomentosa* and *Sclerolaena diacantha* (grey bindii), and the perennial grasses *Austrostipa elegantissima* (feather speargrass) and *Rytidosperma caespitosum* (wallaby grass).

Gradational associations

PXLS changes abruptly into the surrounding Eucalypt, false bluebush woodland (EFBW, #53) at the margins of depressions where the peneplain resumes.

Land systems

PXLS is a minor habitat type in the Caiguna and Charlina land systems.

87 Sedgeland drainage focus (SEDF)

Sampling

3 inventory sites

General information

SEDF is described for the first time but is only provisionally described because there was insufficient sampling. It is an infrequent habitat in drainage foci often associated with outer and inner aprons of granite exposures in the south of the survey area. Soils are Red shallow loams and Shallow sandy duplexes between low (usually <5 m high) granite pavements.

Physiognomy and composition of vegetation

SEDF is characterised by the presence of sedges typically belonging to the genus *Lepidosperma*. *L. drummondii** was most frequently observed. SEDF typically occurs as a moderately close to closed (≥25% PFC) sedgeland–shrubland complex with emergent trees. Sedges may dominate the understorey in moderately close to close (25–50% PFC) homogenous stands or be co-dominant as scattered to moderately close (>10–25% PFC) clumps with *Triodia scariosa* (spinifex). *Dianella revoluta* (blueberry lily) is also common in this stratum. Occurring over and among the sedges are moderately close (>20–30% PFC) emergent tall and mid shrubs. Species such as *Acacia acuminata* (jam), *A. triptycha*, *Dodonaea* spp., *Melaleuca elliptica* (granite bottlebrush), *M. uncinata* (broom bush), *Pimelea* spp. and *Santalum acuminatum* (quandong) are common and in areas locally dominant, but no species consistently dominates foci. Eucalypts – such as *E. calycogona* subsp. *calycogona* (square-fruited mallee), *E. celastroides** (mirret), *E. cylindrocarpa** (woodline mallee) and/or *E. terebra* (Balladonia gimlet) – also occur as scattered emergent trees or dense stands fringing the foci. Other low shrubs frequently present as isolated individuals include *Calytrix tetragona* (common fringe-myrtle) and *Scaevola spinescens* (currant bush).

* Also known from Keighery et al. (1993)

Gradational associations

SEDF is a distinctive habitat type which usually has clearly defined boundaries. It is often surrounded by Eucalypt, false bluebush woodland (EFBW, #53) when not abutting granitic rises or pavements.

Land systems

SEDF is a minor habitat type in the south of the survey in land systems – such as Balladonia, Charlina, Cowalinya, Dundas and Sedgeman – that have granitic pavements on which drainage foci may occur.

Drainage focus supporting a sedgeland–shrubland complex associated with a granite pavement in the Charlina land system

88 Thicket: dodonaea (THKD)

Sampling

1 inventory site

General information

THKD is described for the first time. It is only provisionally described because there was insufficient sampling. It was only encountered in the north-west of the survey area in drainage foci near Lake Deborah. It has topographic similarities to Drainage focus eucalypt woodland (DFEW, #82) and occurs in drainage foci adjacent to granitic pediments, and structural similarities to the gilgai associations in DFEW. It is different though, because of the scarcity of eucalypts among the thickets, the prominence of monospecific stands of *Dodonaea viscosa* subsp. *angustissima* rather than species from the family Scrophulariaceae, and soil type. Soil is a Calcareous loamy earth.

Physiognomy and composition of vegetation

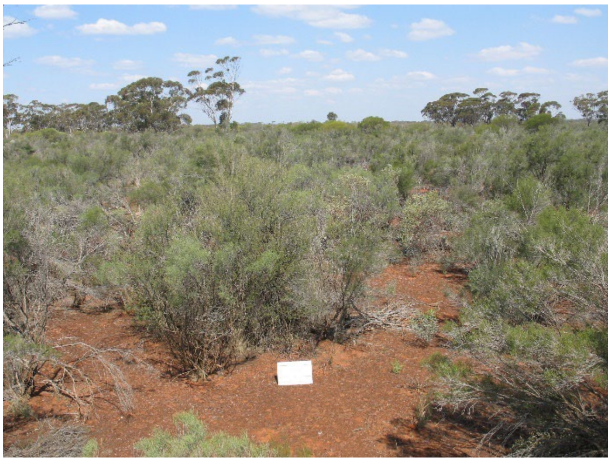
THKD occurs as closed (>50% PFC) monospecific thickets of *Dodonaea viscosa* subsp. *angustissima* in the tall and mid shrub strata. *Acacia jennerae* and *Senna artemisioides* subsp. *filifolia* (desert cassia) are also common through these strata. Isolated to very scattered *Eucalyptus salmonophloia* (salmon gum) fringe and emerge through the thickets. Other species within the low shrub and perennial grass strata are only a minor component.

Gradational associations

THKD is a distinctive habitat type that has clearly defined boundaries, though gradation may occur at the edges of some drainage foci with surroundings supporting Plain eucalypt, eremophila woodland (PEEW, #59) or Lakeside (sand sheet) eucalypt woodland with shrubs (LSES, #64).

Land systems

THKD is a minor habitat type in the Doney and Lake Deborah land systems in the north-west of the survey.



A closed thicket of *Dodonaea viscosa* subsp. *angustissima* in a drainage focus in the Doney land system

References

Addison J (2012) 'Rangeland condition monitoring – plants of the southern rangelands', *Rangelands Memo*, 2(1):12–14.

Beard JS (1972) 'The vegetation of the Kalgoorlie area, Western Australia', *1:250,000 Vegetation Series*, Vegmap Publications, Sydney.

Beard JS (1975) 'The vegetation of the Nullarbor area, Explanatory notes to Sheet 4', *Vegetation survey of Western Australia, 1:1,000,000 Vegetation Series*, University of Western Australia Press.

Beard JS (1976) 'The vegetation of the Boorabbin and Lake Johnston areas: map and explanatory memoir', 2nd edn, *Vegetation survey of Western Australia, 1:250,000 Vegetation Series,* Vegmap Publications, Perth, WA.

Beard JS (1980) 'A new phytogeographic map of Western Australia', *Western Australian Herbarium Research Notes*, 3:37–58.

Beard JS (1981) 'The vegetation of the Swan area, Explanatory notes to Sheet 7', *Vegetation survey of Western Australia, 1:1,000,000 Vegetation Series*, University of Western Australia Press.

Beard JS (1990) *Plant life of Western Australia*, Kangaroo Press, Kenthurst, New South Wales.

Bettenay E (1983) 'Chapter 13 – Western Region (II)', in *Soils: an Australian viewpoint*, CSIRO Division of Soils, Melbourne.

Bowman DMJS, Boggs GS and Prior LD (2008) 'Fire maintains an *Acacia aneura* shrubland–*Triodia* grassland mosaic in central Australia', *Journal of Arid Environments*, 72:34–47.

Bowler JM (1976) 'Aridity in Australia: age, origins and expression in aeolian landforms and sediments', *Earth-Science Reviews*, 12:179–310.

Brooker MIH and Kleinig DA (2001) *Field guide to eucalypts. Volume 2, South-western and southern Australia*, 2nd edn, Bloomings Books.

Bunbury B (1997) *Timber for gold: life on the Goldfields woodlines, 1899–1965,* Talking history with Bill Bunbury, Fremantle Arts Centre Press, Fremantle, Western Australia.

Burnside DG (1985) 'Local flora and fauna – degradation, recovery and management', in *The Goldfields and its environment*, WA School of Mines Seminar, November 1985, pp. 1–19.

Burnside D, Holm A, Payne A and Wilson G (1995) *Reading the rangeland: a guide to the arid shrublands of Western Australia*, Department of Agriculture, Western Australia.

Burrows ND, Burbidge AA, Fuller PJ and Behn G (2006) 'Evidence of altered fire regimes in the Western Desert region of Australia', *Conservation Science Western Australia*, 5(3):272–284.

Christian CS and Stewart GA (1953) 'General report on survey of Katherine–Darwin Region, 1946', *Land Research Series No. 1*, CSIRO, Canberra.

Clarke JDA (1994) 'Evolution of the Lefroy and Cowan palaeodrainage channels, Western Australia', *Australian Journal of Earth Sciences: An International Geoscience Journal of the Geological Society of Australia*, 41(1):55–68.

Clarke MF, Avitabile SC, Brown L, Callister KE, Haslem A, Holland GJ, Kelly LT, Kenny SA, Nimmo DG, Spence-Bailey LM, Taylor RS, Watson SJ and Bennett AF (2010) 'Ageing mallee eucalypt vegetation after fire: insights for successional trajectories in semi-arid mallee ecosystems', *Australian Journal of Botany*, 58:363–72.

Cole MM (1992) 'The vegetation of the greenstone belts of Western Australia', in Roberts BA and Proctor J (eds) *The Ecology of Areas with Serpentinized Rocks, A World View*, Kluwer Academic Publishers, Netherlands, pp. 343–373.

Collins SL, Glenn SM and Gibson DJ (1995) 'Experimental analysis of intermediate disturbance and initial floristic composition: decoupling cause and effect', *Ecology*, 76:486–92.

Craven LA, Lepschi BJ, Broadhurst L and Byrne M (2004) 'Taxonomic revision of the broombush complex in Western Australia (Myrtaceae *Melaleuca uncinata s.l.*)', *Australian Systematic Botany*, 17:255–271.

Curry PJ, Payne AL and Wilcox DG (1983) 'Suggested descriptive terms for classes of foliar cover in arid zone shrublands', *Range Management Newsletter*, 83(3):12–13.

Curry PJ (1986) 'Fire induced changes in grazed wanyu (*Acacia ramulosa*) shrubland on the Victoria Sandplain, Western Australia', in Joss PJ, Lynch PW and Williams OB (eds) *Rangelands: a resource under siege, Proceedings*, 2nd International Rangelands Congress, Adelaide, Australia, 1984, pp. 597–598.

Curry PJ, Payne AL, Leighton KA, Hennig P and Blood DA (1994) 'An inventory and condition survey of the Murchison River catchment, Western Australia', *Technical bulletin 84*, Department of Agriculture, Western Australian Government.

DAFWA (Department of Agriculture and Food, Western Australia) (2006) *Fire management for the southern shrublands and Pilbara pastoral rangelands: best practice guidelines*, Department of Agriculture and Food, Western Australian Government.

Davis J, Pavlova P, Thompson R and Sunnucks P (2013) 'Evolutionary refugia and ecological refuges: key concepts for conserving Australian arid zone freshwater biodiversity under climate change', *Global Change Biology*, 19:1970–1984.

DBCA (Department of Biodiversity, Conservation and Attractions) (2019) *Conservation codes for Western Australian flora and fauna*, DBCA, Western Australian Government.

DBCA (Department of Biodiversity, Conservation and Attractions) (2020) *Priority ecological communities for Western Australia* (Version 30), DBCA, Western Australian Government.

Diels L (1906) 'Die Pflanzenwelt von West-Australien südlich des Wendekreises', *Vegn. Erde* 7, Leipzig.

Doepel JJG (1973) 'Norseman, Western Australia: sheet SI 51–2 international index', *1:250,000 geological series – explanatory notes*, Geological Survey of Western Australia, Perth.

Egler FE (1954) 'Vegetation science concepts. I. Initial floristic composition, a factor in old-field vegetation development', *Vegetatio*, 4:412–417.

Environment Australia (2000) *Revision of the interim biogeographic regionalisation for Australia (IBRA) and the development of version 5.1 – summary report*, Department of Environment and Heritage, Australian Government.

Fitzgerald K (1976) 'The effects of fire on productivity and stability in arid pastoral areas', *Working Papers*, 4th Australian Arid-Zone Research Conference, July 1976, Kalgoorlie, WA.

Fletcher WJ (1991) *Impact and production of feral goats in an arid mulga shrubland*, MSc thesis, University of Western Australia.

Fletcher WJ (1995) 'Yerilla Goat Grazing Study, 1989–1990, a summary of results, findings and observations', *Miscellaneous publication 20/95,* Department of Agriculture, Western Australian Government.

Fox J (1992) 'The problem of scale in community resource management', *Environmental Management*, 16:289–297.

Friedel MH, Nelson DJ, Sparrow AD, Kinloch JE and Maconochie JR (1993) 'What induces central Australian arid zone trees and shrubs to flower and fruit?', *Australian Journal of Botany*, 41:307–319.

Galloway P, van Gool D, Griffin T, Stuart-Street A, Pathan S and Laycock J (in press) 'Western Australian Soil Groups: a key to classify soils', *Resource management technical report 427*, Department of Primary Industries and Regional Development, Western Australian Government.

Gardner CA and Bennetts HW (1956) *The toxic plants of Western Australia*, West Australian Newspapers Ltd, Perth.

Gosper CR, Yates CJ, Prober SM and Parsons BC (2012) 'Contrasting changes in vegetation structure and diversity with time since fire in two Australian Mediterranean plant communities', *Austral Ecology*, 37:164–174.

Gosper CR, Prober SM and Yates CJ (2013a) 'Multi-century changes in vegetation structure and fuel availability in fire-sensitive eucalypt woodlands', *Forest Ecology and Management*, 310:102–109.

Gosper CR, Yates CJ and Prober SM (2013b) 'Floristic diversity in fire sensitive eucalypt woodlands shows a 'U'-shaped relationship with time since fire', *Journal of Applied Ecology*, 50:1187–1196.

Graetz RD and Wilson AD (1984) 'Saltbush and bluebush', in Harrington GN, Wilson AD and Young MD (eds) *Management of Australia's rangelands*, CSIRO, Melbourne.

Griffin TJ (1989) 'Widgiemooltha, 'Western Australia: sheet SH 51–14 international index', 2nd edn, *1:250,000 geological series – explanatory notes*, Geological Survey of Western Australia, Perth.

Hacker RB (1979) *Studies of the ecology and range condition of two arid ecosystems*, PhD thesis, University of New South Wales.

Harvey JM (2014) *Regional variability in Salmon Gum (Eucalyptus salmonophloia) woodlands of south-western Australia, with particular focus on the Great Western Woodlands*, MPhil thesis, Curtin University, Western Australia.

Hnatiuk RJ, Thackway R and Walker J (2009) 'Vegetation', in *Australian soil and land survey field handbook,* 3rd edn, National Committee on Soil and Terrain, CSIRO Publishing, Melbourne.

Hodgkinson KC and Griffin GF (1982) 'Adaptation of shrub species to fires in the arid zone', in Barker WR and Greenslade PJM (eds) *Evolution of the Flora and Fauna of Arid Australia*, Peacock Publications, South Australia.

Hopkins AJM and Robinson CJ (1981) 'Fire induced structural change in a Western Australian Woodland', *Australian Journal of Ecology*, 6:177–188.

Jennings JN and Mabbutt JA (1977) 'Physiographic Outlines and Regions', in Jeans DN (ed) *Australia – A Geography*, Sydney University Press.

Judd S, Watson JEM and Watson AWT (2008) 'Diversity of a semi-arid, intact Mediterranean ecosystem in south-west Australia', *Web Ecology*, 8:84–93, doi.org/10.5194/we-8-84-2008.

Keally I (1991) 'Management of inland arid and semi-arid woodland forest of Western Australia', in McKinnell FH, Hopkins ER and Fox JED (eds) *Forest Management in Australia*, Surrey Beatty and Sons, Chipping Norton.

Keighery GJ, Milewski, AV and Hnatiuk RJ (1992) 'Vegetation and flora', in Keighery GJ and Hall NJ (eds) *The biological survey of the Eastern Goldfields of Western Australia Part 8, Kurnalpi–Kalgoorlie study area,* Records of the Western Australian Museum Supplement Number 41, Western Australian Museum, Perth.

Keighery GJ, Newbey KR and Hall NJ (1993) 'Vegetation and flora', in Hall NJ and Keighery GJ (eds) *The Biological Survey of the Eastern Goldfields of Western Australia Part 9, Norseman–Balladonia Study Area*, Records of the Western Australian Museum Supplement Number 42, Western Australian Museum, Perth.

Keighery GJ, Milewski AV and Hall NJ (1995) 'Vegetation and flora', in Burbidge AA, Hall NJ, Keighery GJ and McKenzie NL (eds) *The Biological Survey of the Eastern Goldfields of*

Western Australia Part 12, Barlee–Menzies Study Area, Records of the Western Australian Museum Supplement Number 49, Western Australian Museum, Perth.

Landsberg J, James CD, Maconochie J, Nicholls AO, Stol J and Tynan R (2002) 'Scale-related effects of grazing on native plant communities in an arid rangeland region of South Australia', *Journal of Applied Ecology*, 39:427–444.

Lay BG (1976) 'Fire in the pastoral country', *Journal of Agriculture, South Australia*, 79(1):9–14.

Laut P, Heyligers PC, Keig G, Loffler E, Margules C, Scott RM and Sullivan ME (1977) *Environments of South Australian – Province 7 – Western Pastoral*, CSIRO Division of Land Use Research, Canberra.

Lowry DC (1970) 'Geology of the Western Australian part of the Eucla Basin', *Bulletin 122*, Geological Survey of Western Australia.

Meissner RA and Coppen R (2013) 'Flora and vegetation of the greenstone ranges of the Yilgarn Craton: Credo Station', *Conservation Science Western Australia*, 8(3):333–343.

Mitchell AA, McCarthy RC and Hacker RB (1979) 'A range inventory and condition survey of part of the Western Australian Nullarbor Plain, 1974', *Technical bulletin 47*, Department of Agriculture, Western Australian Government.

Mitchell AA and Wilcox DG (1994) *Arid shrubland plants of Western Australia*, revised edition, University of Western Australia Press, Perth.

Morton SR and Stafford Smith M (1994) 'Integration of production and conservation in Australia's rangelands' in Morton SR and Price P (eds) *R & D for sustainable use and management of Australia's rangelands*, Land and Water Resources Research and Development Corporation, Occasional Paper Series No. 06/93, Canberra.

Muir BG (1977) *Biological Survey of the Western Australian Wheatbelt, Part 2, Vegetation and Habitat of Bendering Reserve*, Records of the Western Australian Museum, Supplement 3, Western Australian Museum, Perth.

Murphy B, Paron P, Prior L, Boggs G, Franklin D and Bowman D (2010) 'Using generalized autoregressive error models to understand fire–vegetation–soil feedbacks in a mulga-spinifex landscape mosaic', *Journal of Biogeography*, 37:2169–2182.

Nano CEM, Clarke P and Pavey C (2011) 'Fire regimes in arid hummock grasslands and Acacia shrublands', in Bradstock RA, Gill AM and Williams RJ (eds) *Flammable Australia*, CSIRO Publishing, pp. 195–214.

National Committee on Soil and Terrain (2009) *Australian soil and land survey field handbook*, 3rd edn, CSIRO Publishing, Melbourne.

Newbey KR and Hnatiuk RJ (1984) 'Vegetation and flora', in *The Biological Survey of the Eastern Goldfields of Western Australia Part 2, Widgiemooltha–Zanthus Study Area*, Records of the Western Australian Museum Supplement Number 18, Western Australian Museum, Perth.

Newbey KR and Hnatiuk RJ (1985) 'Vegetation and flora', in Dell J, How RA, Newbey KR and Hnatiuk RJ (eds) *The Biological Survey of the Eastern Goldfields of Western Australia Part 3, Jackson–Kalgoorlie Study Area*, Records of the Western Australian Museum Supplement Number 23, Western Australian Museum, Perth.

Newbey KR and Hnatiuk RJ (1988) 'Vegetation and flora', in How RA, Newbey KR, Dell J, Muir BG and Hnatiuk RJ (eds) *The Biological Survey of the Eastern Goldfields of Western Australia Part 4, Lake Johnston–Hyden Study Area*, Records of the Western Australian Museum Supplement Number 30, Western Australian Museum, Perth.

Newbey KR, Keighery GJ and Hall NJ (1995) 'Vegetation and flora', in Keighery GJ, McKenzie NL and Hall NJ (eds) *The Biological Survey of the Eastern Goldfields of Western Australia Part 11, Boorabbin–Southern Cross Study Area*, Records of the Western Australian Museum Supplement Number 49, Western Australian Museum, Perth.

Nicholas AMM, Franklin DC and Bowman DMJS (2009) ‘Co-existence of shrubs and grass in a semi-arid landscape: a case study of mulga (*Acacia aneura*, Mimosaceae) shrub-lands embedded in fire-prone spinifex (*Triodia pungens*, Poaceae) hummock grasslands’, *Australian Journal of Botany*, 57:396–405.

Nicolle D and Conran JG (1999) ‘Variation in the *Eucalyptus flocktoniae* Complex (Myrtaceae) and the description of four new taxa from southern Australia’, *Australian Systematic Botany*, 12:207–239.

Northcote KH (1983) ‘Chapter 16 – Central Southern Region (I)’, in *Soils: an Australian viewpoint*, CSIRO Division of Soils, Melbourne.

Nulsen RA, Bligh KJ, Baxter IN, Solin EJ and Imrie DH (1986) ‘The fate of rainfall in a mallee and heath vegetated catchment in southern Western Australia’, *Australian Journal of Ecology*, 11:361–371.

NVIS (National Vegetation Information System) (2017) *Australian Vegetation Attribute Manual: National Vegetation Information System, Version 7.0*, Bolton MP, deLacey C and Bossard KB (eds), Department of the Environment and Energy, Canberra.

O’Donnell AJ, Boer MM, McCaw WL and Grierson PF (2011a) ‘Vegetation and landscape connectivity control wildfire intervals in unmanaged semi-arid shrublands and woodlands in Australia’, *Journal of Biogeography*, 38:112–124.

O’Donnell AJ, Boer MM, McCaw WL and Grierson PF (2011b) ‘Climatic anomalies drive wildfire occurrence and extent in semi-arid shrublands and woodlands of south-west Australia’, *Ecosphere*, 2(11): article 127.

O’Donnell AJ, Boer MM, McCaw WL and Grierson PF (2014) ‘Scale-dependent thresholds in the dominant controls of wildfire size in semi-arid woodlands of south-west Australia’, *Ecosphere*, 5(7): article 93.

Payne AL, Curry PJ and Spencer GF (1987) ‘An inventory and condition survey of rangelands in the Carnarvon Basin, Western Australia’, *Technical bulletin 73*, Department of Agriculture, Western Australian Government.

Payne AL, Mitchell AA and Holman WF (1988) ‘An inventory and condition survey of rangelands in the Ashburton River catchment, Western Australia’, *Technical bulletin 62*, Revised edition. Department of Agriculture, Western Australian Government.

Payne AL, Mitchell AA and Hennig P (1998a) ‘Land systems of the Kambalda area and surrounds’, Private report prepared for WMC Resources Ltd, Natural Resource Management Services, Department of Agriculture, Western Australian Government.

Payne AL, Van Vreeswyk AME, Pringle HJR, Leighton KA and Hennig P (1998b) ‘An inventory and condition survey of the Sandstone – Yalgoo – Paynes Find area, Western Australia’, *Technical bulletin 90*, Department of Agriculture, Western Australian Government.

Pickett STA, Collins SL and Armesto JJ (1987) ‘Models, mechanisms and pathways during succession’, *The Botanical Review*, 53:335–371.

Preece PB (1971) ‘Contributions to the biology of mulga I. Flowering’, *Australian Journal of Botany*, 19:21–38.

Pringle HJR, Van Vreeswyk AME and Gilligan SA (1994) ‘An inventory and condition survey of the north-eastern Goldfields, Western Australia’, *Technical bulletin 87*, Department of Agriculture, Western Australian Government.

Prober SM, Thiele KR, Rundel PW, Yates CJ, Berry SL, Byrne M, Christidis L, Gosper CR, Grierson PF, Lemson K, Lyons T, Macfarlane C, O’Connor MH, Scott JK, Standish RJ, Stock WD, van Etten EJB, Wardell-Johnson GW and Watson A (2012) ‘Facilitating adaptation of biodiversity to climate change: a conceptual frame-work applied to the world’s largest Mediterranean-climate woodland’, *Climatic Change*, 110:227–248.

Prober SM, Yuen E, O'Connor MH and Shultz L (2013) *Ngadju kala: Ngadju fire knowledge and contemporary fire management in the Great Western Woodlands*, CSIRO Ecosystem Sciences, Floreat, Western Australia.

Raiter KG, Prober SM, Hobbs RJ and Possingham HP (2017) 'Lines in the sand: quantifying the cumulative development footprint in the world's largest remaining temperate woodland', *Landscape Ecology*, 32(10):1969–1986.

Raiter KG, Prober SM, Possingham HP, Westcott F and Hobbs RJ (2018) 'Linear infrastructure impacts on landscape hydrology', *Journal of Environmental Management*, 206:446–457.

Rangelands NRM (2015) *Field guide to common grasses of the southern rangelands*, Rangelands NRM, Perth, Western Australia.

Reith F, Verboom W, Pate J and Chittleborough D (2019) 'Collaborative involvement of woody plant roots and rhizosphere microorganisms in the formation of pedogenetic clays', *Annals of Botany*, 124(6):1007–1018.

Russell P and Fletcher W (2003) 'Relative palatability of selected perennial plants in the southern rangelands of Western Australia; Results of survey of rangeland practitioners', *Range Management Newsletter* 3:1–18.

Schoknecht NR, Tille PJ and Purdie BR (2004) 'Soil-landscape mapping in south-Western Australia: an overview of methodology and outputs', *Resource Management technical report 280*, Department of Agriculture, Western Australian Government.

Society for Range Management (1991) 'SRM recommends new range terminology', in *Trailboss News*, Supplement to *Journal of Range Management*, September 1991.

Specht RL (1970) 'Vegetation', in Leeper GW (ed) *Australian Environment*, 4th edn, Melbourne University Press, Melbourne.

Stephens D (2018) 'Australian seasonal rainfall zone maps' (produced by D. Stephens from Agrometeorology Australia) in Hoyle F and Murphy D (eds) *Soil Quality: 3 Soil Organic Matter*, SoilsWest Perth.

Thackway R and Cresswell ID (1995) *An Interim Biogeographic Regionalisation for Australia: a framework for establishing the national system of reserves, Version 4.0*, Australian Nature Conservation Agency, Canberra.

Tille P (2006) 'Soil-landscapes of Western Australia's rangelands and arid interior', *Resource management technical report 313*, Department of Agriculture and Food, Western Australian Government.

Tinley KL (1991) 'Vegetation and Site types', in *Ecological Survey of Abydos – Woodstock Reserve, Western Australia*, Records of the Western Australian Museum, Supplement No. 37, Western Australian Museum, Perth.

Tongway DJ (1994) *Rangeland Soil Condition Assessment Manual*, CSIRO, Canberra.

Tongway DJ and Greene RSB (1989) *The role of pastoral management on soil productive potential in rangelands*, Final report to the National Soil Conservation Program, CSIRO Division of Wildlife and Ecology, Canberra.

Tongway DJ, Ludwig JA and Whitford WG (1989) 'Mulga log mounds: fertile patches in the semi-arid woodlands of eastern Australia', *Australian Journal of Ecology*, 14:263–268.

Tongway DJ and Ludwig JA (1990) 'Vegetation and soil patterning in semi-arid mulga lands of eastern Australia', *Australian Journal of Ecology*, 15:23–34.

Tongway DJ and Ludwig JA (1997) 'The conservation of water and nutrients within landscapes', in Ludwig J, Tongway D, Fruedenberger D, Noble J and Hodgkinson K (eds) *Landscape Ecology: Function and Management, Principles from Australia's Rangelands*, CSIRO Publishing, Melbourne.

Tyler IM and Hocking RM (2001) 'A revision of the tectonic units of Western Australia', in *Annual Review, Geological Survey of Western Australia*, 2000–2001, pp. 33–44.

Underwood EC, Klausmeyer KR, Cox RL, Busby SM, Morrison SA and Shaw MR (2009) 'Expanding the global network of protected areas to save the imperiled Mediterranean biome', *Conservation Biology*, 23:43–52.

Van Vreeswyk AME, Payne AL, Leighton KA and Hennig P (2004) 'An inventory and condition survey of the Pilbara region, Western Australia', *Technical bulletin 92*, Department of Agriculture, Western Australian Government.

Verboom WH and Pate JS (2013) 'Exploring the biological dimension to pedogenesis with emphasis on the ecosystems, soils and landscapes of south-western Australia', *Geoderma*, 211–212:154–183.

Waddell PA, Gardner AK and Hennig P (2010) 'An inventory and condition survey of the Western Australian part of the Nullarbor region', *Technical bulletin 97*, Department of Agriculture and Food, Western Australia Government.

Wasson RJ (1982) 'Landform development in Australia', in Barker WR and Greenslade PJM (eds) *Evolution of the Flora and Fauna of Arid Australia*, Peacock Publications, South Australia.

Watson A, Judd S, Watson J, Lam A and Mackenzie D (2008) *The extraordinary nature of the Great Western Woodlands*, The Wilderness Society, Perth, Western Australia.

WAH (Western Australian Herbarium) (1998–) *Florabase—the Western Australian Flora*, Department of Biodiversity, Conservation and Attractions, Western Australian Government.

Westoby M, Walker B and Noy-Meir I (1989) 'Opportunistic management for rangelands not at equilibrium', *Journal of Range Management*, 42(4):266–274.

Wilcox DG and McKinnon EA (1972) *A report on the condition of the Gascoyne catchment*, Department of Agriculture, Western Australian Government.

Williams JE (2002) 'Fire regimes and their impacts in the mulga (*Acacia aneura*) landscapes of central Australia', in Russell-Smith J, Craig R, Gill AM, Smith R and Williams JE (eds) *Australian fire regimes: contemporary patterns (April 1998—March 2000) and Changes since European settlement*, Department of the Environment and Heritage, Canberra.

Wright BR and Clarke PJ (2007) 'Resprouting response of *Acacia* shrubs in the Western Desert of Australia – fire severity, interval and season influence survival', *International Journal of Wildland Fire*, 16:317–323.

Wu H, Zhang J, Stanton R, An M, Liu DL and Lemerle D (2011) 'Allelopathic effect of *Eucalyptus dundasii* on germination and growth of ryegrass and barley grass', *Allelopathy Journal*, 28(1):87–94.

Yates CJ, Hobbs RJ and Bell RW (1994) 'Landscape-scale disturbances and regeneration in semi-arid woodlands of south-western Australia', *Pacific Conservation Biology*, 1:214–221.

Yates CJ, Norton DA and Hobbs RJ (2000) 'Grazing effects on plant cover, soil and microclimate in fragmented woodlands in south-western Australia: implications for restoration', *Austral Ecology*, 25:36–47.

Zhang J, An M, Wu H, Liu DL and Stanton R (2012) 'Chemical composition of essential oils of four *Eucalyptus* species and their phytotoxicity on silverleaf nightshade (*Solanum elaeagnifolium* Cav.) in Australia', *Plant Growth Regulation*, 68:231–237.