PRIORITY THREAT MANAGEMENT FOR PILBARA SPECIES OF CONSERVATION SIGNIFICANCE

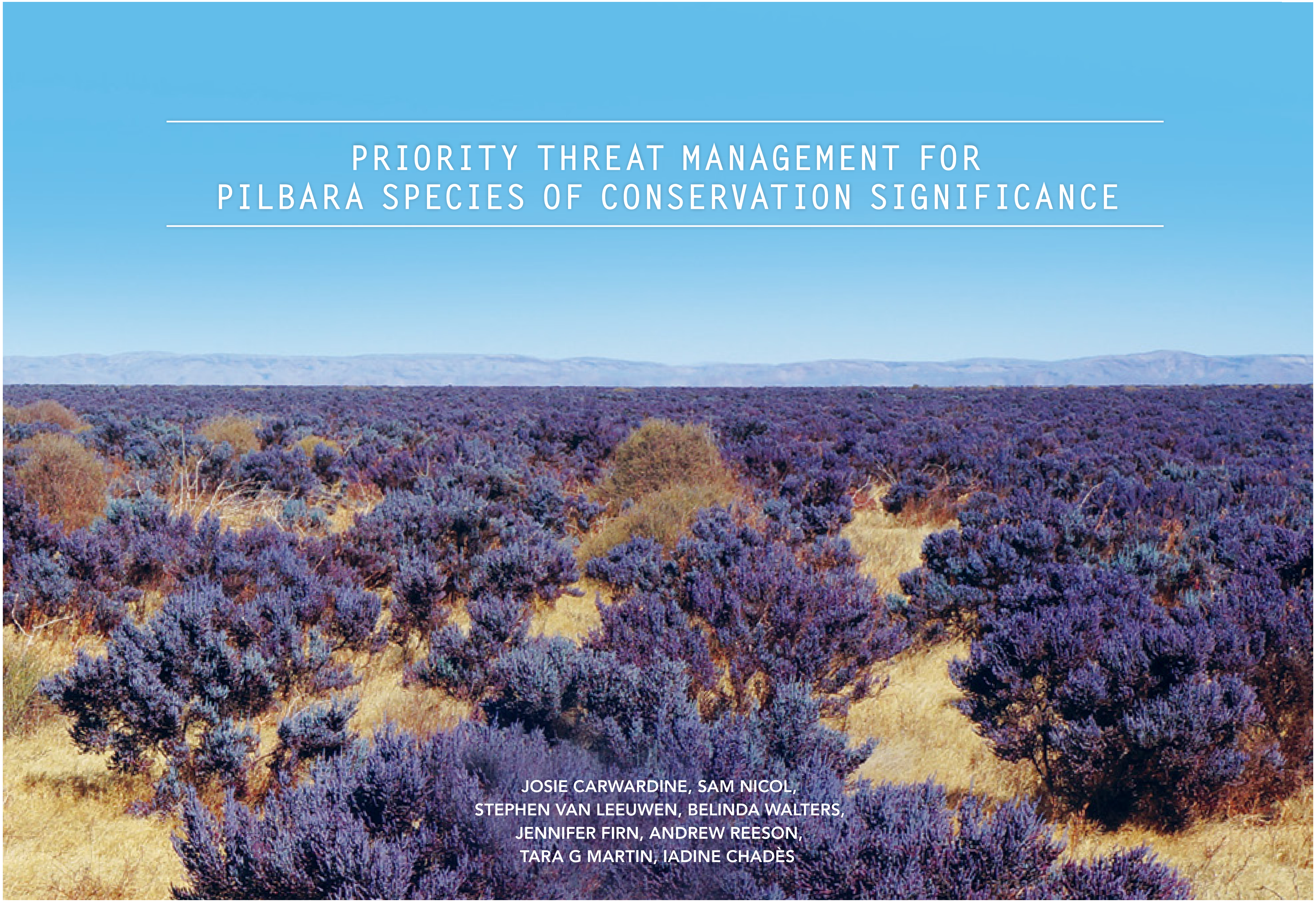

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PHOTO BELOW *The Pilbara Leaf-nosed Bat (Rhinonicteris aurantia) is a cryptic and poorly known species found across the Pilbara and northern Gascoyne bioregions. The bat has very specific maternal roost environmental requirements which appear to be rare across the two bioregions although the species is known to inhabit suitable abandoned mine workings in the east Pilbara.*
PHOTO BY *Mark Cowan, DPaW.*

PRIORITY THREAT MANAGEMENT FOR PILBARA SPECIES OF CONSERVATION SIGNIFICANCE

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PHOTO BELOW *Tall Mulla Mulla (Ptilotus nobilis) on stony spinifex gibber plains adjacent to the Fortescue Marsh.*
PHOTO BY *Jeff Pinder, DPaW.*

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PHOTO BELOW Aerial view across the saline bed of the Fortescue Marsh looking south from near Minga Well on Mulga Downs Station across to the Hamersley Range escarpment.
PHOTO BY Louisa Bell, DPaW.

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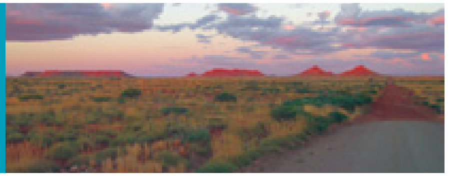


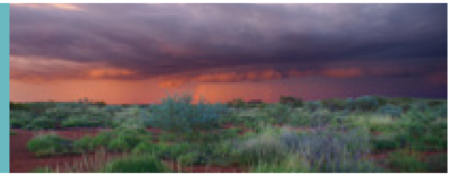


PHOTO BELOW Spinifex shrublands on Red Hill Station, West Pilbara.
PHOTO BY Leanne Corker, Red Hill Station.

PHOTO BELOW Pilbara trudgenii, *an endemic long-lived daisy restricted to banded ironstone screes and cliffs of the higher elevation mountains throughout the Hamersley Range.*
PHOTO BY Stephen van Leeuwen, DpaW.

EXECUTIVE SUMMARY

This project provides a costed and appraised set of management strategies for mitigating threats to species of conservation significance in the Pilbara IBRA bioregion of Western Australia (hereafter 'the Pilbara'). Conservation significant species are either listed under federal and state legislation, international agreements or considered likely to be threatened in the next 20 years.

Here we report on the 17 technically and socially feasible management strategies, which were drawn from the collective experience and knowledge of 49 experts and stakeholders in the ecology and management of the Pilbara region. We determine the relative ecological cost-effectiveness of each strategy, calculated as the expected benefit of management to the persistence of 53 key threatened native fauna and flora species, divided by the expected cost of management. Finally we provide decision support to assist prioritisation of the strategies on the basis of ecological cost-effectiveness.

The ecosystems within the ancient and arid landscape of the Pilbara are under growing pressure from a number of threats including increases in total grazing pressure by native, feral and domestic ungulates and herbivores, invasion by exotic plants and animals, predation by feral predators and altered fire regimes. Recent biodiversity surveys have highlighted the impacts of threats and the paucity of existing knowledge about the Pilbara's flora and fauna. Prior to our prioritisation study, there was no region-wide assessment of which management strategies provide the best investments for securing the Pilbara's threatened biodiversity. Further, this study provides the first broad-scale estimate of which species are likely to be lost without effective action. The outputs of this work are designed to help guide decision-making and further planning and investment in biodiversity conservation in the Pilbara.

Our approach involved gathering data from existing studies and literature, and supplementing this with expert and stakeholders' knowledge through a structured elicitation approach. Given the lack of empirical data on threatening processes and the ecology of many Pilbara species, our approach draws heavily on the knowledge of experts. Experts and stakeholders in the Pilbara's biodiversity, industry, natural resource management and policy-making attended a workshop. The strategies they identified directly addressed threats which were considered to have a high potential for broad, significant impacts on the persistence of 53 species of concern over the next 20 years and for which feasible management strategies could be defined.

For each of the 17 strategies, participants estimated the feasibility of implementation (0–100%) and the expected increase in the probability of functional persistence (0–1, 'biodiversity benefit') of the species in the Pilbara over the next 20 year period. Functional persistence was defined as the presence of a species within its natural range at high enough population levels to perform its ecological function. The economic cost of each strategy over 20 years was estimated during the workshop and refined during post-workshop discussions. Cost-effectiveness was then calculated for each strategy for the entire Pilbara region and the four IBRA subregions of the Pilbara by dividing the expected improvements in species persistence by the expected costs. A sensitivity analysis revealed that the cost-effectiveness ranks were relatively robust to changes in the benefit estimates of up to ±30%.

PHOTO BELOW The Black-footed Rock Wallaby (Petrogale lateralis) is now locally extinct in the Pilbara having previously been recorded from Depuch Island, west of Port Hedland.
PHOTO BY Jiri Lochman, Lochman Transparencies.

THE KEY FINDINGS FROM THE REPORT ARE:

- **Without management intervention, 13 of the 53 (25%) conservation significant species are likely to be functionally lost from the Pilbara in the next 20 years (probability of persistence <0.5).**
  Among the fauna species most likely to be lost from the region are critical weight range mammals such as the greater bilby and spectacled hare-wallaby. Plant species at risk include a range of herbaceous shrubs and herbs such as the De Grey saltbush and Muccan fuchsia. According to our analysis, habitat loss and altered fire regimes pose the key threat to the 53 species we considered. Without effective management action, many other species are at risk of declines.
- **The top three most cost-effective strategies for the entire Pilbara are: (1) management of feral ungulates; (2) sanctuaries; and (3) cat management.**
  Each of the three top-ranking strategies had average expected costs of under $1m/year. Feral ungulate management was relatively cheap and highly feasible. Sanctuaries offer high benefits at a small cost but would only offer protection over a small area compared to other strategies. Cat management was considered to have a high benefit but was rated to have the lowest chance of success (49%) of all the strategies. Although the cost was relatively high ($4m/year), the strategy 'habitat identification, protection and restoration' was the individual strategy with the highest expected benefit.
- **The total cost of implementing all strategies over the next 20 years was estimated at $348 million, roughly $17.5 million/year.**
  The highest benefit was obtained by implementing all strategies. It was estimated that implementation of these strategies would result in all species having a likelihood of persistence greater than 50%. Seven of these species would have a likelihood of persistence greater than 90%. If it was not possible to fund all strategies, it would be possible to secure all species with a probability of persistence greater than 50% by funding domestic herbivore management, fire management and research, and the establishment and management of one mainland sanctuary and island sanctuaries with a combined cost of $95.2 million over 20 years (or $4.76 million/year), although it should be acknowledged that protecting a species in a sanctuary does not equate to functional protection across its current range.
- **At a subregional level, feral ungulate and/or domestic herbivore management and cat management were the most cost-effective strategies, but these varied between IBRA subregions.**
  In Chichester and Fortescue the top three ranked strategies were (i) feral ungulate management, (ii) domestic herbivore management and (iii) combined feral ungulate and domestic herbivore management. In Hamersley, it was most cost-effective to implement (i) feral ungulate management, (ii) cat management and (iii) combined feral ungulate and domestic herbivore management. In Roebourne, it was most cost-effective to implement (i) feral ungulate management, (ii) domestic herbivore management and (iii) cat management.

PHOTO BELOW Hearson Cove, a popular recreation site on the Burrup Peninsula. The Pistol Ranges in the background are part of the Murujuga National Park. PHOTO BY Vicki Long, Astron Environmental Services.

- **There is a need to improve knowledge sharing amongst stakeholders in the Pilbara, as agreed by participants at the workshop.** With the rapid development of the Pilbara, vast numbers of ecological surveys and research projects are generating a valuable dataset of the threatened species of the Pilbara. However most of the data generated are not accessible and there is a need to collate this information and make it publicly available. Data sharing would improve knowledge of species ranges and critical habitats and could be used to design more effective targeted management strategies. This would have the added benefit of reducing the cost of some management actions by focusing management in areas where target species are present.
- **Investment in the identified management strategies has benefits other than the conservation of threatened species.** Examples of additional benefits may include protecting species and communities that are not currently listed as threatened; enhancing ecologically sustainable mining, tourism and pastoral activities; job creation; improved carbon sequestration, soil health, water quality, and drought tolerance; improved resilience to changes in climate; and meeting the conservation and land management goals of Indigenous communities in the Pilbara.
- **The implementation of strategies involves stakeholders, further planning and adaptive management.** Ongoing stakeholder engagement, extension and participation are required to ensure this prioritisation effort has a positive impact in affecting on-ground decision making and planning. Due to uncertainties in the outcomes and impacts of management options, strategies should be implemented as part of an adaptive management, 'learning by doing' program.

A number of caveats apply to our recommendations. Due to a lack of empirical data on the responses of threatened species to threats and management strategies, our estimates of probability of persistence are largely based on the expert judgement of workshop participants. Further, the benefits of the proposed strategies were evaluated only in terms of their benefits to threatened species within the Pilbara bioregion. The impacts of threats and strategies on non-listed species, oceanic and/or marine species (sea turtles and cetaceans), migratory species (shore birds and waders), species that occur nearby but outside the Pilbara (northern marsupial mole), or listed Threatened Ecological Communities were outside the scope of this report. Threats were assessed based on existing conditions in the Pilbara. Long-term future threats, such as climate change were not considered in the analysis. Threats with unknown consequences, such as, the impact of changed hydrology on short-range endemics, and subterranean fauna (troglofauna and stygofauna) were only evaluated using the existing limited knowledge of their impacts on known conservation significant species. Costs and feasibility of strategies were also based on estimates by experts and stakeholders.

This report provides a region-wide picture of the conservation significant flora and fauna most at risk of extinction, and provides a cost-effective approach to selecting threat management strategies in the Pilbara to best protect them.

The Pilbara has the potential to build upon its reputation as a region with exceptional biodiversity values in addition to exceptional mineral resources. The opportunity exists to implement a region-wide conservation strategy to protect the Pilbara conservation significant species and conserve the diverse biota of this unique and ancient region and we provide some of the critical information required to do so.

PHOTO BELOW Gnamma on a granite outcrop in the Chichester subregion of the Pilbara.
PHOTO BY Outback Ecology.

1

THE PILBARA: VALUES, THREATS AND CONSERVATION

The Pilbara region of Western Australia is a vast and ancient landscape, covering over 178 000 km² and is home to approximately 50,000 people. Dubbed the 'engine room of Australia' due to the region's vast mineral wealth, the Pilbara is also home to a suite of iconic and fascinating plants and animals, many of which are found nowhere else on earth.

The Pilbara IBRA region (Interim Biogeographic Regionalisation of Australia, (Thackway and Cresswell 1995)) hereafter 'the Pilbara', consists of four subregions: Chichester, Fortescue, Hamersley and Roebourne (*Figure 1*) (Commonwealth of Australia 2000–2004, ALA 2010). The Pilbara is characterised by extensive arid coastal plains, rolling spinifex grasslands on stony pavements and inland mountain ranges with roughed escarpments and deep gorges. Vegetation is predominantly hummock (*Triodia* spp.) grasslands with scattered emergent snappy gums and wattle shrublands, although low mulga woodlands with an herbaceous layer and bunch grasses dominate toward the south of the region (Beard 1975, Commonwealth of Australia 2000–2004).

Indigenous Australians have inhabited the Pilbara for tens of thousands of years and the region is home to the most abundant collection of rock engravings in the world (Bednarik 2002). The rock engravings, called petroglyphs, include depictions of human-like figures amongst the oldest ever recorded, and animals that no longer inhabit the region, including the Tasmanian tiger. The region remains important for the art, history and current culture of Indigenous Australians.

Since the 1960s, the economy has been driven overwhelmingly by the extraction of the Pilbara's legendary reserves of iron ore and offshore petroleum/natural gas centred on the towns of Tom Price, Newman, Paraburdoo, Pannawonica, Karratha/Dampier and Port Hedland. Along with mining, approximately 65% of the Pilbara's area is used by the commercial cattle grazing industry (Department of the Environment, Water, Heritage and the Arts 2008). The region also boasts a growing tourist market centred on the key attractions of Karijini National Park, Millstream-Chichester National Park and the Dampier Archipelago.

The Pilbara is also known for its biodiversity values (McKenzie *et al.* 2009). The Pilbara is home to a wide variety of endemic species adapted to its arid environment, including a dozen species of *Acacia*, numerous other plant species, several reptiles, and many species of subterranean fauna (including stygofauna and troglofauna; invertebrates which live underground in the caves, vugs and groundwater aquifers).

The Pilbara landscape supports one of the richest reptile assemblages in the world (Doughty *et al.* 2011), and is also one of the last bastions for some of Australia's most iconic vertebrate species, such as the northern quoll, mulgara and greater bilby. A spectacular array of plant species are found in the Pilbara, including the near endemic Millstream fan-palm and over 125 species of *Acacia*.

No mammal species are endemic to the Pilbara bioregion although a few are almost so, including the Pilbara leaf-nose bat, western pebble-mound mouse, little red kaluta, Rothschild's rock wallaby, the Pilbara ningaui and two undescribed species of planigale (small carnivorous marsupial). A suite of small reptiles (Pepper *et al.* 2013) are endemic to the Pilbara while one of Australia's largest reptiles, the Pilbara olive python is almost so.

Figure 1 The Pilbara and its four subregions in Western Australia (DPaW 2013)

The remoteness of the Pilbara means that many of the region's species are poorly understood or unknown to science, with new species frequently being described. For example 12 new species of *Acacia* were described in 2008 (Maslin and van Leeuwen 2008), and recent surveys of subterranean ecosystems have revealed remarkably diverse assemblages of subterranean invertebrates (troglofauna and stygofauna), notable for their local endemism and exceptionally high beta diversity (Eberhard and Humphreys 2005).

Cessation of traditional burning practices, invasion, predation and competition from pests and weeds, exploitation of mineral resources and pastoralism in the Pilbara has resulted in widespread declines in regional biota (Woinarksi *et al.* 2000). Of the region's original mammal fauna, 15% are now extinct, and 42 of the region's 88 vegetation types have no formal protection within the conservation estate (McKenzie *et al.* 2009). While the rapid development of the Pilbara may impact deleteriously on the flora and fauna of region, it also provides impetus and potentially the resources and opportunity to address long-standing threats to biodiversity.

PHOTO BELOW Samphire seedlings reestablishing following inundation of the Fortescue Marsh.
PHOTO BY Jeff Pinder, DPaW.

In the following sections, we highlight the elements of the Pilbara most relevant to this analysis, i.e., its ecological values and biodiversity, the threats faced by the Pilbara biota and the current conservation efforts in the region. We then provide a rationale for a prioritisation approach to address the threats facing the conservation significant species of the Pilbara.

1.1 ECOLOGICAL VALUES

The ancient, arid landscapes of the Pilbara have been evolving for 2.5 billion years, making them some of the oldest in the world.

Across the vast area of the Pilbara are elements of tropical, desert and semi-arid southern rangeland biota, as well as many locally endemic species (McKenzie *et al*. 2009, Pepper *et al*. 2013). The terrestrial ecosystems of the Pilbara can be broadly classified by their subregions: the coastal plains and offshore islands of the Roebourne subregion, the Pilbara tablelands of the Chichester and Hamersley subregions, and the low-lying alluvial flats of the Fortescue subregion. Being an arid landscape, the river systems, including, De Grey, Turner, Yule, Robe, and Fortescue, are prominent features of the landscape. These river systems are characterised by predominantly episodic flows driven by monsoonal rainfall over summer. During the dry periods, these rivers are reduced to pools providing important refugia for aquatic fauna (Dobbs and Davies 2009, Pinder *et al*. 2010). Five Pilbara wetlands are recognised as being of national significance: Fortescue Marsh, Karijini Gorges, the Leslie Saltfields system and the Millstream Pools (McKenzie *et al*. 2009).

The vegetation of the Roebourne subregion is predominantly mixed grass and *Acacia* shrublands with some spinifex (*Triodia* spp.) uplands. It is characterised by coastal plains, which consist of low relief headlands, deltas, barrier islands and lagoons with many kinds of shorelines — mangroves, samphire flats, tidal algal mats, sandy beaches and rocky shores. While we do not consider all species confined to the offshore islands, many of these islands are predator-free and maintain populations of species of high conservation value. On the mainland, the relatively undisturbed Burrup Peninsula (Murujuga) near Karratha is of particular value. The Burrup protects a high diversity of restricted plants, with vegetation assemblages that are generally distinct from elsewhere on the Pilbara mainland. The peninsula also harbours a diverse fauna including 20 terrestrial mammals, 121 bird species, 47 herpetofauna species (Western Australian Planning Commission 2009), and is also a centre for endemism in land snails (Stankowski and Johnson 2014). The Burrup, especially those parts within the recently proclaimed Murujuga National Park, protect populations of Rothschild's rock wallaby and the Pilbara olive python (Kendrick and Stanley 2001, Department of Environment and Conservation 2013).

The Hamersley Ranges and the undulating Chichester Ranges divide the Pilbara tablelands from the south and north respectively, with the alluvial plains, salt marsh and associated ephemeral freshwater wetlands and riparian systems of the Fortescue Valley separating them. The gorges of the Hamersley Ranges protect relict populations of land snails, skinks and plants, and the calcrete aquifers of the plains have high species endemism and diversity

PHOTO TOP *Fire in a spinifex shrubland on Red Hill Station, West Pilbara.*
PHOTO BY *Darcie Corker, Red Hill Station.*

PHOTO BOTTOM *Burnt wattle shrubland on Red Hill Station, West Pilbara*
PHOTO BY *Darcie Corker, Red Hill Station.*

of stygofauna and troglofauna that remain largely undescribed (Kendrick 2001b, Halse *et al.* 2014). The Chichester Ranges support populations of 51 vertebrate species including iconic critical weight range mammals such as the mulgara, greater bilby and spectacled hare-wallaby (Kendrick and McKenzie 2001). Bat species are well represented in the Chichester subregion, including populations of Pilbara leaf-nosed bat, ghost bat, northwestern long-eared bat and little northwestern free-tailed bat (McKenzie and Bullen 2009). The subregion is also a hotspot for reptiles (16 bioregional endemic species recorded) and small mammals (Kendrick and McKenzie 2001, Gibson and McKenzie 2009, Doughty *et al.* 2011).

The Pilbara has an arid and variable climate with irregular episodic rainfall events. Sources of permanent water are of high ecological value. The Pilbara tablelands support five wetlands of national significance, as well as 12 wetlands of regional significance (Lane *et al.* 2001). The Fortescue subregion contains the Millstream wetlands, which extend for more than 40km and include large, deep pools and extensive wetland and riparian communities. The aquatic invertebrate community is extremely diverse and rich in endemics for an arid area (Pinder *et al.* 2010). The Millstream Fan-palm is restricted to the calcareous wetland at Millstream and a few other similar wetlands scattered across the Chichester and Hamersley subregions. The Millstream aquifer contains a largely unstudied assemblage of stygofauna thought to contain many undescribed endemics (Kendrick 2001a). The region also contains the nationally significant Fortescue Marsh, which episodically supports massive-scale waterbird breeding events (BirdLife International 2013).

For a more in depth background to the Pilbara, interested readers can refer to van Vreeswyk *et al.* (2004) and McKenzie *et al.* (2009).

1.2 THREATS

Over-grazing, increasingly frequent wildfires, exotic species introductions promoting predation and competition and changed hydrological regimes have combined to degrade the Pilbara at rates equivalent to other arid pastoral regions of Australia (McKenzie *et al.* 2009). Pastoral use and mining, as well as changed fire frequency and intensity, has altered vegetation cover and soil profiles (Woinarksi *et al.* 2000). Extraction of water to fuel the growing demands of the mining industry is a more recent and less well understood threat, however there is a need to manage extraction limits and discharge of excess water that will not adversely affect the Pilbara's biota (Department of Water 2013a-c, Charles et al. 2013).

FIRE

Much of the vegetation of the Pilbara is well adapted to fire, and many species require fire as part of their life cycle. However, when fires are too frequent or intense, negative ecosystem impacts occur, such as the loss of the understory growth that provides many reptiles and mammals with protection from predators and the loss of food resources, such as seeding grass for graminivorous birds. Aboriginal burning practices in the Pilbara involved burning patches of vegetation creating of a mosaic of burnt and unburnt patches, a practice that regulates fuel loads and manages against large intense fires (Allan and Southgate 2002). Changes in land

PHOTO TOP Camel browsing on Fitzroy wattle (Acacia ancistrocarpa) on Roy Hill Station.
PHOTO BY Hamish Robertson, DPaW.

PHOTO BOTTOM Droughtmaster cattle grazing in a Pilbara Jam (Acacia citrinoviridis) tall shrubland on Red Hill Station.
PHOTO BY Leanne Corker, Red Hill Station.

cover as well as an increased ignition risk promoted by the region's railway network have led to more frequent intense wildfires in the hummock grasslands of the Pilbara (Allan and Southgate 2002). Altered fire regimes have been implicated as one of the causes of decline and extinctions of medium-sized mammals in arid Australia (Burbidge and McKenzie 1989, Allan and Southgate 2002).

OVER-GRAZING AND FERAL HERBIVORES

The first white settlements in the region in the 1860s were established for the purposes of sheep stations (Western Australian Land Information Authority 2013), and pastoralism was the dominant economic activity in the region until the discovery of mineral deposits in the late 1800's. Although pastoralism now plays a lesser role in the region's economy than mining, most of the Pilbara is gazetted as pastoral land. The conservation and land management practices implemented by the bioregion's pastoralists are therefore of high importance to conserving and managing the region's biota.

Early settlers introduced a range of grazing animals now considered feral, including pigs (*Sus scrofa*), rabbits (*Oryctolagus cuniculus*), camels (*Camelus dromedarius*), donkeys (*Equus asinus*) and horses (*Equus ferus caballus*) (Burbidge and McKenzie 1989). There is also a population of unmanaged cattle (*Bos primigenius*). Some of these invasive herbivores occur across all tenures, including national parks (Burbidge and McKenzie 1989) while others, like pigs and rabbits, are now confined to localised and restricted habitats such as riparian environs along the De Grey River and alluvial flats associated with the Fortescue Marsh, respectively. The main impacts of introduced herbivores in the Pilbara are compaction and erosion of soil, loss of grazing-sensitive plant species, reduced native grass biomass, introduction of weed seeds and trampling of seedlings and mature plants. Widespread loss of vegetation caused by invasive herbivores can lead to a reduction in vegetation structure and thus habitat and food resources for native animals, and the loss of vegetation cover can expose small native animals to increased risk of predation (Martin 2010). Trampling and high livestock numbers also leads to eutrophication of waterways, erosion and sedimentation of wetlands and riparian habitats, including the nationally significant listed wetlands of the Pilbara (Burbidge and McKenzie 1989, Kendrick 2001a, Kendrick and McKenzie 2001, Pinder *et al.* 2010).

INTRODUCED PREDATORS

Feral cats (*Felis catus*) are widespread across the Pilbara while red foxes (*Vulpes vulpes*) appear to be confined to the coastal plain of the Roebourne subregion and may move further inland along the frontages of some of the larger drainage systems such as the Robe and De Grey rivers. Together they are responsible for range reductions and population declines of many native animals and in particular, small to medium sized mammals in many parts of Australia (Burbidge and McKenzie 1989, Woinarksi *et al.* 2011). For example, predation of juvenile Pilbara olive pythons by foxes and cats is suspected to be a problem for populations in the coastal Pilbara region. Foxes and cats also prey on the python's food sources (Pearson 2003). The role of top predators such as dingoes, goannas and raptors in exerting control over the interactions between cats,

PHOTO TOP Floodwaters replenishing groundwater supplies for the River Red Gums (Eucalyptus camaldulensis) along Red Hill Creek immediately adjacent to the Red Hill Homestead.
PHOTO BY Leanne Corker, Red Hill Station.

PHOTO BOTTOM Ephemeral pools on a creekline near Onslow in the far west of the Pilbara. Note the bright green shrubs on the bank immediately above the river channel and pool are Parkinsonia (Parkinsonia aculeata), a Weed of National Significance (WONS).
PHOTO BY Linda Anderson, DAFWA.

foxes and their prey is an area of growing interest (Allen *et al*. 2013, Ritchie *et al*. 2013). The regular baiting of dingoes and wild dogs as a measure to protect livestock may exacerbate the problem of introduced feral cats, as cat behaviour appears to be suppressed by dingoes (Ritchie *et al*. 2013). Cane toads are currently an irregular, episodic arrival in the region, typically invading in freight or shipping containers from the Kimberley, Darwin or eastern states. The establishment of cane toads in the Pilbara has the potential to reduce populations of native predators as well as many reptiles, small frogs and invertebrates (Shine 2010).

INVASIVE PLANTS

Invasion of exotic plant species is another threat facing the Pilbara and is often associated with inappropriate fire and grazing regimes as well as mining operations. Compared to other regions of Australia, the exotic flora of the Pilbara (103 taxa) is relatively small, representing only 6% of the Pilbara's total flora (Keighery 2010). However the threat of weed incursions is on the rise with a 20% increase recorded from 2004 to 2010 (Keighery 2010). Of the 103 weeds identified by Keighery (2010), 14 species occur across the region at a landscape scale, altering fire patterns, modifying soil characteristics, or competing directly with native species. A further 21 species pose a threat to particular habitats, especially wetlands and islands. Major weeds currently impacting on landscapes and biodiversity values or which pose a future risk (Department of Parks and Wildlife 2013) include mesquite (*Prosopis* sp), buffel grass (*Cenchrus ciliaris* also known as *Pennisetum ciliare*), birdwood grass (*Cenchrus setiger*), kapok bush (*Aerva javanica*), ruby dock (*Acetosa vesicaria*), and potentially bellyache bush (*Jatropha gossypiifolia*), leucaena (*Leucaena leucocephala* subsp. *leucocephala*), raintree (*Albizia lebbeck*) and Caribbean stylo (*Stylosanthes hamata*).

HYDROLOGICAL CHANGE

The growth in the mining industry presents new challenges for water management within the region (Department of Water 2013a,c). Mine dewatering removes groundwater and can create permanent surface flows if discharged directly into ephemeral drainage systems. This has impacts both above and below the surface.

Below the surface, dewatering may affect the rich groundwater dependent ecosystems of the Pilbara. The Pilbara has been identified as an international hotspot for stygofauna (groundwater dwelling) species (Boulton *et al*. 2003, Eberhard and Humphreys 2005). The stygofauna of the Pilbara remain poorly documented and the extent of the impacts of changed hydrology are unknown (Boulton *et al*. 2003).

On the surface, the presence of permanent water or changed flow regimes in such an arid setting can alter the ecological composition of aquatic-dependent species. This is particularly relevant to aquatic invertebrates, as many invertebrates are adapted to intermittent flows (Bunn and Arthington 2002). Abstracted groundwater that discharges into existing permanent water bodies may alter water quality or promote invasive species (Bunn and Arthington 2002). Permanent water on the surface (from mine dewatering or other sources, such as stock watering points (Fensham and Fairfax 2008)) may also attract terrestrial vertebrates,

PHOTO LEFT A Dingo (Canis lupus dingo) searching for prey along the banks of Coondiner Pool, Roy Hill Station.
PHOTO BY Hamish Robertson, DPaW.

PHOTO RIGHT Wild Dogs and Dingoes are present throughout the Pilbara. They are a noteworthy problem for the pastoral industry however their impacts on biodiversity are unclear as interaction with Cats and Foxes may actually reduce predator pressure for medium-sized mammals.
PHOTO BY Fortescue Marsh Cat baiting Team, DPaW.

and may support increased populations of introduced pest species in arid areas (Fensham and Fairfax 2008).

The Pilbara Water Resource Assessment was established in 2012 to help ensure scarce water resources are efficiently and equitably managed into the future (Charles *et al.* 2013). This assessment is reviewing the Pilbara's water resources and estimating the effect of possible future climates and proposed developments on the region's surface and groundwater resources. It will also investigate impacts on water dependent ecosystems. Concurrently with this assessment by CSIRO, the Western Australian Department of Water also undertook a water supply strategy assessment for the Pilbara that provides early assessment and support for further planning of new water supply options in the medium and long-term. This assessment focused on the three coastal schemes of the West Pilbara, Port Hedland and Onslow, and provides an overview of existing and projected regional water demands and supply (Department of Water 2013b).

MINING

Mining has been a part of the Pilbara's history since early settlement, with the name of the region originating from the Pilbara Gold reserve in 1885. Today mining is a significant industry in the Pilbara, representing 38% of Western Australia's Gross Regional Product (GRP) and 6% of Australia's Gross Domestic Product (GDP) (Briggs and McHugh 2013). Iron Ore, Liquefied Natural Gas and Solar Salt are the key resources under extraction and exploration with investments estimated to date in these industries at over $100 billion.

The mining industry has direct impacts on the region's flora and fauna including the loss and alteration/fragmentation of habitat. Indirect impacts result from the construction of roads, railways and infrastructure, growing use of water resources and altered hydrological regimes, contamination of water and soil resources, and altered fire regimes with an increase in unmanaged anthropomorphic ignitions.

AGRICULTURE

Owing to the Pilbara's arid environment, irrigated agriculture in the region has been localised and small-scale. The Northern Australian Taskforce found the potential for sustainable expansion of irrigated agriculture in the Pilbara to be low, but political and economic interest in the proposition of northern Australia as a 'food bowl' of Australia remains (Stone 2009). Similarly the Western Australia state government through the Pilbara Water Opportunities Program and Pilbara Hinterland Agricultural Development Initiative (PHADI) (Baston and Grylls 2013) is also investigating and investing significant resources and revenue ($12.5m) in the development of irrigated agricultures schemes in the Pilbara utilizing excess mine water. The level of water extraction required for large-scale agricultural development in the region may lead to devastating impacts on its ecology, especially of ephemeral riparian systems and extensive alluvial plains where irrigated crops may be grown (Stone 2009).

TOURISM EXPANSION

The Pilbara is increasingly recognised for its natural values, and as such, the region has experienced an increase in tourism (Pilbara Development Commission 2011). The DPaW regulates ecotourism within the conservation estate at present, but inadequate regulation on other land tenures and at entry points could lead to negative impacts on biodiversity including increased risk of fire, the introduction of exotic species and associated fragmentation and pressure on sensitive communities from infrastructure developments.

1.3 CURRENT CONSERVATION MANAGEMENT

Three national parks (Karijini, Millstream Chichester and Murujuga) along with three Nature Reserves (Mungaroona Range, Great Sandy Islands and the Dampier Archipelago), one Conservation Parks (Cane River) and five portions of ex-pastoral lease (Mardie, Mt Florence, Meentheena, Mt Minnie and Nanutarra) that are managed for conservation, protect elements of the Pilbara's biodiversity (*Figure 2*). At present approximately eight percent of the Pilbara is captured within the formal protected area network. In July 2015, several additional portions of pastoral lease will be added to the Pilbara's protected area network when areas are relinquished from leases. These relinquishments will include portions of Hillside, Roy Hill, Mulga Downs, Marillana, Juna Downs, Hamersley, Rocklea, Karratha and Pyramid Stations. These additions to the Pilbara's protected area network will increase the area protected to about 10%.

Outside of the protected area estate, management initiatives include the Pilbara Corridors project (*www.rangelandswa.com.au/688/pilbara-corridors-project*), which is funded over five years by the Australian Governments Biodiversity Fund. The project aims to address key threats to biodiversity including feral herbivores, weeds and fire across tenures and amongst a range of managers and stakeholders (e.g. Traditional Owners and pastoralists) in the Fortescue River catchment. Further weed management targeted at mesquite, a Weed of National Significance, across the region is co-ordinated by the Pilbara Mesquite Management Committee (*www.pilbaramesquite.com.au*).

Specific area management by DPaW occurs in the vicinity of the Fortescue Marsh as part of offset commitments by the Fortescue Metals Group to the Commonwealth and Western Australian government for environmental approvals associated with addressing residual impacts from the Cloudbreak and Christmas Creek mines and associated East-West railway. Threat management for conservation is also addressed by the Pilbara DPaW Nature Conservation Strategy and the Rangelands WA NRM strategy for the Pilbara.

Despite these efforts, the current management regime in the region is likely to be insufficient to adequately protect conservation significant species in the face of known and unknown threats. Like many unique and remote regions, conservation management in the Pilbara is hindered by a lack of knowledge on biodiversity. Hence, the Western Australian Government established the Pilbara Biodiversity Survey from 2002 to 2007 (McKenzie *et al.* 2009). This survey unearthed many new species for the region, some of which occur only in the Pilbara.

Figure 2 Distribution of land tenure types in the four subregions of the Pilbara (DAA 2013 and DPaW 2013)

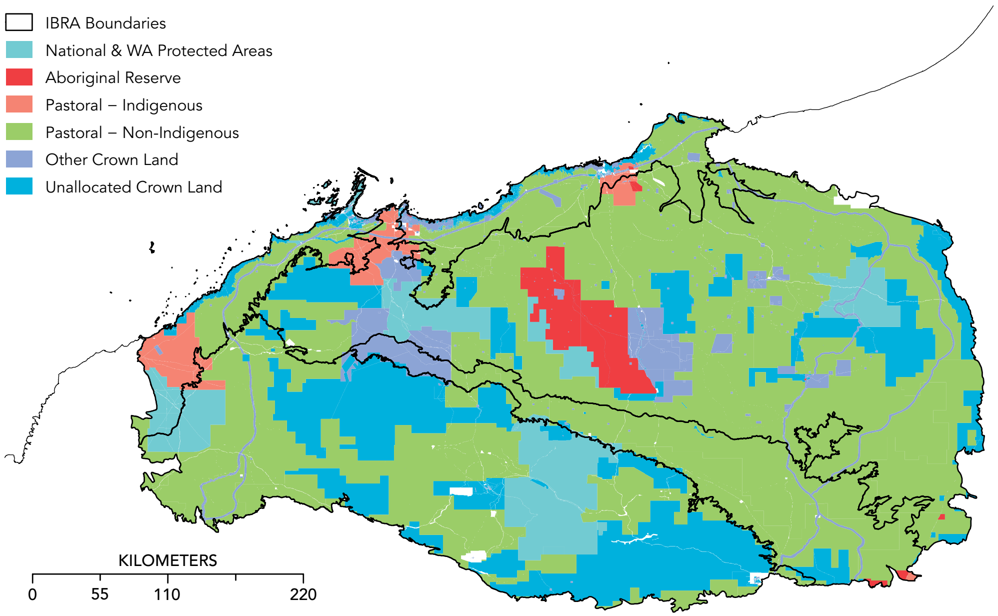


PHOTO BELOW Undulating hills of the Chichester subregion of the Pilbara.
PHOTO BY Outback Ecology.

2 PROJECT AIMS AND SCOPE

PHOTO BELOW The turbidity of Pilbara streams is extremely high following episodic wet season deluges from thunderstorms and tropic cyclone rainfall events.
PHOTO BY Leanne Corker, Red Hill Station.

This project aims to provide a transparent and rational framework to help guide cost-effective investment in conservation within the Pilbara. The approach draws on empirical data and expert information to estimate the expected benefits and costs of conservation strategies, and builds upon previous similar approaches (Possingham *et al.* 2002, Joseph *et al.* 2009, Carwardine *et al.* 2011, 2012, Pannell *et al.* 2012). We evaluate a range of feasible conservation management actions directed at large scale current threats to 53 of the region's most threatened native flora and fauna species.

While the conservation strategies are not new, we contribute new information on their costs, feasibility and likely benefits to threatened and endangered wildlife. For the first time, we also integrate this information into a rational framework to estimate the ecological cost-effectiveness of threat management strategies and therefore provide critical input for defensible decision making.

SPECIFICALLY THE PROJECT AIMS TO:

- Identify key ecological values of the Pilbara and the most threatened flora and fauna species and the habitat they are dependent on.
- Generate a set of costed conservation strategies for addressing threats to these species of concern in the Pilbara.
- Synthesize information regarding threat management strategies for conserving species to prioritise the most cost-effective strategies.
- Provide recommendations and information that are useful to a range of decision-makers, groups and individuals, including Traditional Owners.
- Ensure the approach can consider or contribute to analyses that consider information outside that used in this assessment.

We acknowledge that many factors other than the needs of conservation significant species come into play in conservation decision-making. We recognise the great importance of the priorities of local landowners and users including Indigenous people, pastoralists and the mining and tourism sectors. However, we were unable to collect and analyse comprehensive information on the knowledge, preferences and social considerations and cultural values of these groups. A full stakeholder engagement process was also outside the project scope.

With a focus on 53 species, we highlight just a snapshot of the potential for benefiting biodiversity in the region through managing threats. However it is also likely that our results present a best case scenario in terms of the potential for species losses without effective strategies, as future threats such as climate change may compound the effects of the current threats evaluated in this report.

The intent of this document is not to promote a particular management decision, but to provide usable information on the priority of strategies based on their ecological cost-effectiveness. We envisage this information will be useful to support decision-makers (Traditional Owners, government and non government conservation agencies, mining companies, pastoralists and others) as they plan and implement threat management strategies for conserving the Pilbara's biodiversity.

PHOTO BELOW Thunderstorm on the horizon, Red Hill Station.
PHOTO BY Leanne Corker, Red Hill Station.

3

THE PRIORITY THREAT MANAGEMENT APPROACH

PHOTO BELOW The Chichester Range escarpment near Python Pool, Millstream Chichester National Park.
PHOTO BY Steve Dillon, DPAW.

3.1 PARAMETER DEFINITION AND INFORMATION COLLATION

Applying a threat management prioritisation approach to appraise conservation strategies in the Pilbara required the collation of existing information from the published and grey literature and through extensive consultation with experts and stakeholders.

We collated five types of information:
(1) background literature and a database to identify the conservation significant species inhabiting the Pilbara's four IBRA subregions,
(2) the definition of parameters for the prioritisation approach,
(3) the identification of strategies,
(4) estimates of the costs, expected benefits and feasibility of each of the strategies and
(5) guidance on stakeholder engagement and pathways to ensure the approach is useful to decision makers and managers.

A large portion of the information was collected during a three-day workshop (Perth, March 2013), with participants also involved in follow-up discussion via email and phone.

Potential participants were identified at the outset of the project based on their expected ability to contribute to the range of information required and included: landholders, Indigenous representation (Yamatji Marlpa Indigenous Corporation), park managers, non-government organisations (e.g. Greening Australia WA and WA Conservation Council), university and CSIRO scientists, employees from the Commonwealth Department of the Environment including the Pilbara Taskforce, the WA Department of Parks and Wildlife, Office of the Environmental Protection Agency, Rangelands NRM, the resources industry (Roy Hill, Rio Tinto, BHP Billiton Iron Ore, Atlas Iron and API Management), and environmental consultants. Expertise was specifically sought in the threats to biodiversity in the region, the costs and feasibility of implementing threat management strategies, the ecology of threatened species and their responses to threatening processes and management strategies and people and industries of the region. Potential participants were contacted via email and phone and provided with background to the project and asked about their interest and availability to either attend the workshop or participate through discussion.

Of the 70 experts and stakeholders contacted, a total of 49 participated in the workshop. Participants were contacted after the workshop to check estimated values for the biodiversity benefits and an online forum was established where participants compared, discussed and were able to update their estimates.

COLLATING EXISTING BACKGROUND INFORMATION

A database was collated to identify conservation significant species within Pilbara's four IBRA subregions (*Appendix 1*; *Table A1*). A comprehensive database was initially constructed by identifying and collating all species recorded within these four subregions and drawing them together into one large spreadsheet. These data were collected from the Department of Parks and Wildlife (DPaW) website, NatureMap by the predefined IBRA subregions (*www.naturemap.dec.wa.gov.au*). NatureMap uses many data sources but the primary sources are specimen databases at the Western Australian Herbarium and Western Australia Museum.

PHOTO BELOW Columns of smoke rising from a controlled burn on Red Hill Station.
PHOTO BY Leanne Corker, Red Hill Station.

Federal and State legislation, bilateral migratory bird agreements and international threatened species lists were consulted to identify the conservation significant species within the Pilbara and their current conservation status.

The following federal and state legislation and international agreements were drawn on:

- Environmental Protection of Biodiversity and Conservation Act 1999 (EPBC, Australian Government)
- Wildlife Conservation Act 1950 (Western Australian Government)
- The Convention on the Conservation of Migratory Species
- China-Australia Migratory Bird Agreement
- Japan-Australia Migratory Bird Agreement
- Republic of Korea-Australia Migratory Bird Agreement
- International Union for the Conservation of Nature Red List of Threatened Species.

In addition to formally legislated schedules or lists of threatened species known from the Pilbara the final list of 53 species was augmented with species drawn from DPaW's Priority Flora and Fauna lists (*www.dpaw.wa.gov.au/plants-and-animals/threatened-species-and-communities/listing*). DPaWs priority species lists capture a suite of species that are considered to be threatened but due to a lack of knowledge (e.g. taxonomic uncertainty) or adequate survey have not yet been formally assessed against IUCN Red List criteria.

A review of the published and grey literature was also conducted to identify existing empirical and scientific information, and to highlight gaps that would need to be filled using a structured elicitation process with experts and stakeholders.

PROBLEM AND PARAMETER DEFINITION

The goal of this research was to prioritise feasible threat management strategies based on ecological cost-effectiveness, which is the expected ecological benefits divided by cost. The analysis was restricted to the mainland Pilbara biogeographic region for benefiting 53 terrestrial species of conservation significance. The parameters for the cost-effectiveness include the components of the benefits, feasibility and costs of strategies, and are defined in *Appendix 1*.

EXPERT AND STAKEHOLDER CONSULTATION AND DATA COLLECTION

A list of 53 species for the focus of this study (*Appendix 1*; *Table A1*) was selected from the comprehensive database in consultation with ecological experts. The list includes all species classified as threatened on the EPBC Act (n=12) with the addition of 41 species that experts considered likely to be threatened and likely to be added to the EPBC list in the next 20 years. The final list of species was restricted to those that are known to currently be resident in the Pilbara bioregion. Migratory, nomadic vagrants and marine species were not included.

A structured elicitation approach was used to discuss and refine the parameters and approach and collect the remaining information required at a three-day workshop with a key set of stakeholders and experts. The information collected included defining current threats to the selected list of species, identifying and costing potential management strategies, and estimating the feasibility and the potential benefits of each strategy to the threatened species of the Pilbara.

The workshop was led by a professional facilitator and a team of researchers skilled in decision analysis. Participants were split into small groups, and each group was facilitated by two researchers. Relevant maps and indicative information on existing management and costs were available to help participants with discussion and estimation. Group decisions were collated and presented to the whole group after each elicitation stage where consensus was required.

During the first elicitation phase of the workshop participants identified key threatening processes acting in the Pilbara. Participants then broke into small groups depending on their expertise. These groups suggested possible management strategies (i.e. bundles of management actions) to mitigate each of the threatening processes. The following 17 strategies and combinations of strategies were agreed upon at the workshop (see *Appendix 1*, *Table A2* for more details of the actions that comprise each strategy):

1. Feral ungulate management
2. Domestic herbivore management
3. Combined feral ungulate and domestic herbivore management
4. Fire management (plan and implement adaptively)
5. Fire management (as above) and research
6. Combined domestic herbivore, feral ungulate and fire management
7. Cat management
8. Cat management and research
9. Sanctuaries (enclosures or island)
10. Cane toads management
11. Weed management around key assets
12. Weed biosecurity team
13. Targeted exotic pasture grasses (including buffel grass) through management (contain, control, eradicate) and restoration
14. Combined weed and pasture grasses strategy
15. Hydrology management
16. Habitat identification, protection and restoration
17. Total combined strategy (strategies included 1, 2, 5, 8, 9 to 13, 15 and 16)

The second elicitation phase of the workshop involved estimating the cost and feasibility of each action making up each strategy. Fixed and variable costs were estimated in a range of units, using existing information where available. Two elements of feasibility were collected: the probability of uptake (the likelihood that the strategy would be implemented, taking into account economic, social and political factors) and the probability of success of the strategy (the likelihood that, if implemented, the strategy would be effective, for more details see *Appendix 1*).

The final elicitation phase involved ecological experts estimating the information required for calculating the potential benefit of each strategy. The potential benefit was defined as the summed improvement in the probability of functional persistence of all species over 20 years when implementing the strategy successfully compared with not implementing the strategy. The probability of 'functional persistence' in the landscape was given by the likelihood that a species will persist at levels high enough to achieve their ecological function in 20 years. Every participant estimated benefits individually, first estimating the probability of persistence of each species under a 'baseline scenario' in which no management actions were implemented. Then they estimated the probability of species persistence under each of the individual strategies.

Experts made their first round of estimates, then these were summarised and provided back to experts and they had an opportunity to discuss and revise their estimates (see *Appendix 1* for more details). While all strategies have slightly different treatment areas, we measured the benefit at the scale of the subregions.

PHOTO BELOW Feral Cat with a Button Quail (Turnix velox) on the Fortescue Marsh, August 2012.
PHOTO BY Fortescue Marsh Cat Baiting Team, DPaW.

PHOTO BELOW Cattle watering point on Mulga Downs Station near the Fortescue Marsh.
PHOTO BY Jeff Pinder, DPaW.

3.2 ANALYSIS

ESTIMATING THE POTENTIAL AND EXPECTED BENEFITS AND COSTS FOR EACH STRATEGY

The potential benefit B_i of implementing strategy i in the Pilbara bioregion (or a subregion) was defined by the cumulative difference in persistence probability of all threatened species in the region, with and without implementation of that strategy, averaged over the experts who made predictions for the species:

$$B_i = \sum_{j=1}^{N} \frac{\sum_{k=1}^{M_j} (P_{ijk} - P_{0jk})}{M_j}$$

Where

P_{ijk} is the probability of persistence of species j if strategy i is implemented, estimated by expert k.

P_{0jk} is the probability of persistence of species j if no strategy is implemented (baseline scenario), estimated by expert k.

N is the number of threatened species.

M_j is the number of experts who made predictions for species j.

The total potential benefit was also generated for each subregion by summing only the benefits for the species that occur in that subregion (see *Appendix 1*).

The expected benefit for each strategy was then determined by multiplying the potential benefit by the feasibility score, providing an indication of the likely improvement in persistence across all species in the region if that strategy was implemented. All species were valued equally for conservation.

Feasibility for each action was calculated as the product of the likelihoods of uptake and success. The feasibility of each strategy was calculated by averaging feasibility values across all actions in each strategy, for both the entire region and each subregion.

Cost estimates for each action involved with the 17 strategies were obtained from the stakeholders during the workshop, and were converted to present day values using a present value equation for both the entire region and for each subregion (see *Appendix 1*).

ESTIMATING COST-EFFECTIVENESS OF STRATEGIES

Cost-effectiveness (CE) of each strategy i was computed as the total expected benefit of the strategy, which is the potential Benefit B_i * Feasibility F_i, divided by the expected cost C_i:

$$CE_i = \frac{B_i F_i}{C_i}$$

Cost-effectiveness was calculated for each strategy over the entire region and for each subregion. Strategy 9, sanctuaries, was not applicable for the subregional analysis as it does not involve all subregions. Further information on the calculation of cost-effectiveness is included in *Appendix 1*.

OPTIMAL SPENDING OF LIMITED BUDGETS

Cost-effectiveness analysis using the objective described above can determine a priority ranking of strategies, but it is not designed to identify the optimal bundles of strategies for achieving target levels of species security at minimal cost. This might be useful if decision-makers have the objective of securing the most species possible for any given budget. We define a 'secure' species as a species that is estimated to persist with a probability that exceeds a fixed persistence threshold over 20 years. We use a multi-objective optimisation approach to find the best groups of strategies that 'secure' as many species as possible above three likely persistence thresholds (90%, 75% and 50%) over a range of budget levels (Nemhauser and Ullmann 1969). Contrary to the cost-effectiveness approach, this approach provides a rational way of selecting complementary groups of strategies, i.e. two strategies that secure the same species will not be both selected, even if they are ranked highly in cost-effectiveness. Further information on the calculation of the optimal solutions is included in *Appendix 1*.

PHOTO BELOW Basalt boulder rockpiles of the Burrup Peninsula in Murujuga National Park.
PHOTO BY Steve Dillon, DPaW.

PHOTO BELOW Herd of predominantly droughtmaster cattle on Red Hill Station.
PHOTO BY Leanne Corker Red Hill Station.

4

PRIORITISATION OF THREAT MANAGEMENT STRATEGIES

PHOTO TOP Ephemeral pool on Red Hill Creek.
PHOTO BY Leanne Corker, Red Hill Station.
PHOTO BOTTOM A small Ridge-tailed Monitor (Varanus acanthuru) trapped in a discarded cool drink can.
PHOTO BY Stephen van Leeuwen, DPaW.

4.1 APPRAISAL AND RANKED MANAGEMENT STRATEGIES

Our analysis showed that the cost-effectiveness of strategies varied across the Pilbara region, as well as amongst the four Pilbara subregions. Strategies involving the management of feral ungulates and domestic herbivores and cats tended to be ranked highest, and the establishment of predator proof sanctuaries was also a high priority.

COST-EFFECTIVENESS OF STRATEGIES ACROSS THE REGION

Feral ungulate management was predicted to be the most cost-effective strategy for investment over the entire Pilbara bioregion, followed by implementation of sanctuaries and cat management (*Table 1*). All three top-ranking strategies had average expected costs of under $1m/year over 20 years. Although the expected benefit of feral ungulate management was ranked tenth of the 17 strategies, it was the most cost-effective strategy because it was considered to be comparatively cheap with a high probability of uptake and likelihood of success.

Sanctuaries offer high expected benefits and were considered feasible, but are more than twice as expensive as feral ungulate management, which is why the cost-effectiveness of sanctuaries is lower than feral ungulate management. Note that sanctuaries would only offer protection over a small area compared to other strategies. The cat management strategy had a moderately high benefit but the probability of success was uncertain, with participants predicting only a 49% chance of success over the 20 year management period (the lowest probability of success of all the strategies). For this strategy the high cost-effectiveness was driven predominantly by a relatively low cost.

The strategies with the highest expected benefits were combined strategies. As expected, the highest benefit was obtained by doing all strategies simultaneously, which would cost approximately $17.5m/year over 20 years. The strategy with the next highest benefit was a combined feral ungulate, domestic herbivore and fire management strategy, which had high feasibility and would cost around $4m/year.

Habitat identification, protection and restoration was the individual strategy with the highest expected benefit. Actions within this strategy included maintaining a fixed representation of habitat types and determining important conservation metrics for species such as critical habitat and minimum fragment size for population viability. The cost of this strategy was comparatively high ($4m/year), driven largely by the requirement to maintain a fixed percentage of representative habitats and this reduced the cost-effectiveness of the strategy (ranked ninth of 17 strategies for cost-effectiveness). Participants at the workshop emphasized the importance of collating and sharing existing information on threatened species. Participants commented that information is collected by different parties for individual projects but is not made freely available.

Some of the strategies were predicted to have little known benefits to the species of concern or had particularly low ecological cost-effectiveness. The weed biosecurity team had the lowest expected benefit to biodiversity and the lowest cost-effectiveness of all the strategies. None of the weed management

PHOTO LEFT Dingo on the Fortescue Marsh, August 2012.
PHOTO BY Fortescue Marsh Cat Baiting Team, DPaW.

PHOTO RIGHT A herd of donkeys on the spinifex apron of the Fortescue Marsh, June 2013. Note the donkey towards the centre of the herd is fitted with a GPS collar. This donkey is part of the Judas Donkey Program. The collar facilitates the rapid locating of the herd during regular aerial shooting campaigns.
PHOTO BY Jon Pridham, DPaW.

strategies had very high expected benefits or cost-effectiveness, and even the combined weed management strategy only ranked 11th of 17 in terms of expected benefit. While many participants felt that weeds have an impact on biodiversity, this relationship is poorly understood and hard to directly relate to the likelihood of extinction of many threatened species (Levine *et al.* 2003, Grice 2006, Firn and Buckley 2010). Participants were not optimistic about the likelihood of success of weed management strategies, with the exception of targeted management of exotic pasture grasses around key assets (84%). Although targeted exotic pasture grass management was the most likely weed management strategy to be successful if implemented, it was considered unlikely to be implemented as many exotic pasture grasses are valued by pastoralists as feed for stock (this strategy had the lowest likelihood of uptake at 34%). The combined weed and pasture grasses strategy had the highest cost of all the strategies, other than implementing all strategies.

Cane toads are not yet established in the Pilbara; however, the participants at the workshop included a strategy to carry out research on the potential impact of cane toads in the Pilbara and implement a biosecurity program to prevent cane toad establishment. This strategy ranked second-last in cost-effectiveness, driven largely by a relatively low expected benefit of implementing the program. Participants were generally unconcerned or uncertain about the effects of cane toads on the threatened fauna of the Pilbara, perhaps due to uncertainty about how far toads could spread into the arid areas where many of the threatened species persist (Florance *et al.* 2011). Of the 15 vertebrate experts, eight experts did not rank the strategy or else assumed cane toads would have no effect on the species that they ranked. Of the remaining seven experts, six predicted changes in persistence of 10% or less, and no experts agreed on the species affected (with the exception of two experts predicting an increase in Pilbara olive python persistence of 3% and 5% as a result of cane toad management). One expert predicted 20% increases in persistence of the Pilbara barking gecko and the Airlie island ctenotus if the cane toad strategy was implemented. While cane toads are suspected to have caused declines in northern quoll populations in eastern Australia (Burnett 1997, Shine 2010), only one expert predicted an effect of cane toad management (10% increase in persistence) on Pilbara northern quolls.

The hydrology management strategy was the least expensive strategy and the sixth most cost-effective strategy but had a relatively low expected benefit. The low cost of the strategy led to its cost-effectiveness. While many participants wanted to include the strategy due to the potential impacts of extensive dewatering and discharge for mining activities in the Pilbara, there is uncertainty about the effects of changed hydrology on the threatened species of the Pilbara, and particularly on the subterranean fauna (Boulton *et al.* 2003). Even though the Pilbara is known to contain globally significant numbers of groundwater species (Eberhard and Humphreys 2005), the effects of altering hydrological regimes on stygofauna (Boulton

PHOTO LEFT Dead collared feral cat on the Fortescue Marsh.
PHOTO BY Saul Cowen, DPaW.

PHOTO RIGHT Juvenile Northern Quoll, Red Hill Station Homestead.
PHOTO BY Leanne Corker, Red Hill Station.

et al. 2003) and many short-range endemics (Environmental Protection Authority 2009) are unknown, and this uncertainty made it hard to find experts willing to estimate the benefits of action. Only two experts at the workshop ranked the subterranean fauna, and neither ranked the effects of a hydrology management strategy on these species (both ranked habitat identification, protection and restoration instead). This uncertainty is likely to have affected the cost-effectiveness analysis of the hydrology management strategy.

Sensitivity analysis of the results for the Pilbara bioregion indicated that the top five ranked strategies were robust to changes in the estimated benefits. Increasing or decreasing the benefits of any of the top five strategies by as much as 30% did not change the top six strategies. Similarly the five lowest ranked strategies remained ranked in the lowest six strategies despite changes of up to 30% (*Appendix 2, Table A7–10*).

COST-EFFECTIVENESS OF STRATEGIES ACROSS AND WITHIN SUBREGIONS

At a subregional level, strategies to manage the impacts of large herbivores (feral ungulate and/or domestic herbivore management) were the most cost-effective, along with cat management (*Table 2*). Eight of the top 10 most cost-effective strategies across the subregions of the Pilbara involved control of large herbivores (either feral ungulate management, domestic herbivore management or combined feral ungulate and domestic herbivore management). The remaining two most cost-effective strategies in the top 10 were cat management in two regions, Hamersley and Roebourne.

Feral ungulate management in Fortescue, Roebourne and Hamersley was the most cost-effective (ranked first, second and fourth) and the cheapest strategy to implement ($75K/year to $138K/year). Managing domestic herbivores in Fortescue and Roebourne ranked third and fifth from a cost-effectiveness point of view. The combined strategy of ungulate and domestic herbivore management for Fortescue, Roebourne and Hamersley was also highly cost effective (sixth, eighth and ninth). Finally, the cat management strategy in Roebourne and Hamersley was also cost-effective (seventh and tenth). Management strategies for the Chichester subregion were not ranked amongst the top ten most cost effective strategies, probably because of the comparatively high cost of implementing management strategies over such a large subregion.

The top three strategies within each subregion were as follows:

- In Chichester and Fortescue the top strategies and their regional ranks were feral ungulate management (ranked 14th and first overall, respectively), domestic herbivore management (24th and third respectively) and combined feral ungulate and domestic herbivore management (26th and sixth respectively).
- In Hamersley, it was most cost-effective to implement feral ungulate management (fourth), cat management (tenth) and combined feral ungulate and domestic herbivore management (ninth).
- In Roebourne, it was most cost-effective to implement feral ungulate management (second), domestic herbivore management (fifth) and cat management (seventh).

When accounting for benefits only, implementing the total combined strategy in Hamersley, Chichester and Roebourne provided the highest cumulative expected benefits over 20 years (ranked first, second and fifth) but at the highest costs ($6,044K/year, $7,286K/year and $4,599K/year). Similarly the benefits of the combined strategy ungulate, domestic herbivore and fire management in the subregions Hamersley, Chichester, Roebourne ranked third, fourth and sixth but remained expensive to implement, ranking 30th, 23rd and 13th from a cost-effectiveness point of view.

At a subregional level, sensitivity analysis indicated that the two highest-ranked strategies were robust to increases or decreases in benefit of up to 30%. All of the five highest-ranked strategies at the subregional level were robust to an increase in benefit. Decreasing the benefit marginally decreased the ranking of the third, fourth and fifth-highest strategies at the subregional level, but all strategies would remain ranked in the top 20% of strategies even if the benefit of one strategy was overestimated by as much as 30%. The lowest five strategies were robust to changes in estimated benefit—no strategy changed rank by more than three places even if the benefit of the strategy differed by as much as 30%. Details of how the sensitivity analyses were conducted are shown in *Appendix 2*.

PHOTO BELOW Coolibah (Eucalyptus victrix) is an iconic tree of riparian habitats throughout the Pilbara, often occurring with Red River Gum (E. camaldulensis) on dry expansive Pilbara creek lines.
PHOTO BY Leanne Corker, Red Hill Station.

Table 1 Appraisal of key conservation strategies across the Pilbara—estimated average expected benefits, average costs and cost-effectiveness (CE)

STRATEGY NUMBER	STRATEGY	BENEFIT	% UPTAKE	% PR SUCCESS	EXPECTED BENEFIT 20 YEARS	RANK EXPECTED BENEFIT	EXPECTED COST 20 YEARS	AVERAGE EXPECTED COST/YEAR	COST-EFFECTIVENESS SCORE	CE RANK
1	Feral ungulate management	200.9	98%	88%	172	10	$ 7,787,930	$ 389,396	0.22097	1*
2	Domestic herbivore management	407.1	93%	93%	351	6	$ 24,109,343	$ 1,205,467	0.14578	4*
3	Combined feral ungulate and domestic herbivore management	423.8	95%	91%	366	5	$ 29,853,560	$ 1,492,678	0.12249	5
4	Fire management	340.2	96%	91%	299	8	$ 48,843,348	$ 2,442,167	0.06117	10*
5	Fire management and research	506.6	97%	91%	447	4	$ 53,609,888	$ 2,680,494	0.08336	8*
6	Combined feral ungulate, domestic herbivore and fire management	806.3	96%	91%	701	2	$ 83,463,448	$ 4,173,172	0.08395	7
7	Cat management	315.9	100%	49%	155	12	$ 8,454,890	$ 422,744	0.18310	3*
8	Cat management and research	403.4	100%	53%	214	9	$ 43,568,604	$ 2,178,430	0.04908	11*
9	Sanctuaries (enclosure or island)	365.3	100%	85%	311	7	$ 16,854,626	$ 842,731	0.18424	2
10	Cane toad research and biosecurity	64.3	100%	85%	55	15	$ 32,344,917	$ 1,617,246	0.01688	16*
11	Weed management around key assets	125.7	100%	63%	79	13	$ 40,343,382	$ 2,017,169	0.01947	14*
12	Weed biosecurity team	43.2	100%	60%	26	17	$ 34,078,406	$ 1,703,920	0.00760	17*
13	Targeted exotic pasture grasses management	132.1	34%	84%	37	16	$ 11,625,004	$ 581,250	0.03226	12*
14	Combined weed and pasture grasses strategy	296.7	84%	67%	166	11	$ 86,046,793	$ 4,302,340	0.01926	15
15	Hydrology management	101.4	100%	63%	63	14	$ 6,408,389	$ 320,419	0.09885	6*
16	Habitat identification, protection and restoration	861.2	94%	67%	540	3	$ 79,630,437	$ 3,981,522	0.06780	9*
17	Total combined strategy	1352.7	93%	74%	929	1	$ 348,317,214	$ 17,415,861	0.02667	13

**Indicates a strategy that does not combine more than one strategy and is region-wide*

PHOTO BELOW Dust rising from the Fortescue Metals Group Cloudbreak mine following a mine blast. The foreground is dominated by a samphire shrubland (Tecticornia auriculata) which dominates a large part of the Fortescue Marsh.
PHOTO BY Jeff Pinder, DPaW.

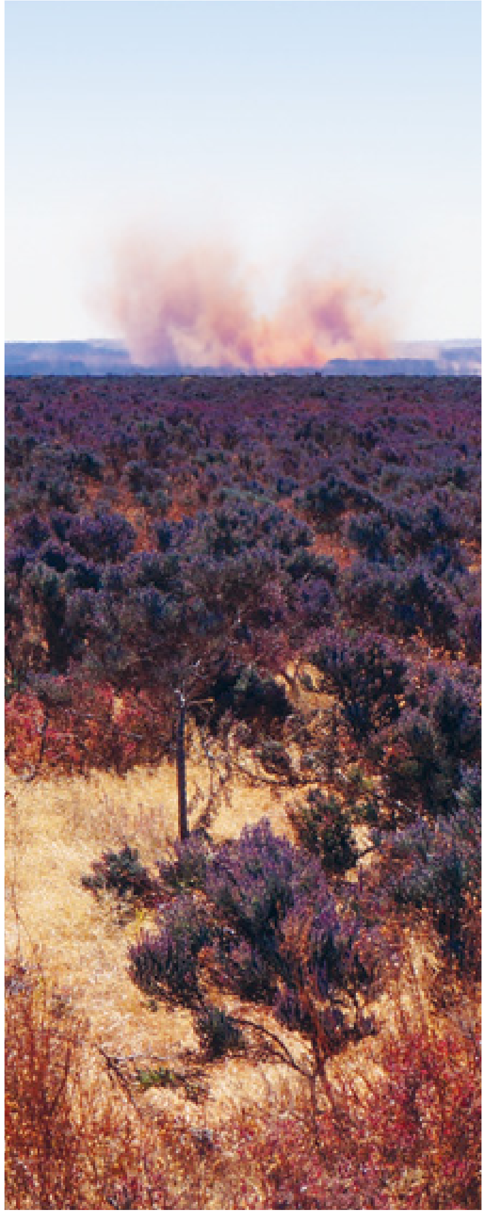


Table 2 Appraisal of key conservation strategies in each of the subregions of the Pilbara—estimated average expected benefits, average costs and cost-effectiveness (CE)

STRATEGY NUMBER	STRATEGY	SUBREGION	EXPECTED BENEFIT 20 YEARS	RANK EXPECTED BENEFIT	EXPECTED COST 20 YEARS	AVERAGE EXPECTED COST/YEAR	COST-EFFECTIVENESS SCORE	CE RANK (ACROSS ALL SUBREGIONS)
1	Feral ungulate management	Chichester	91	39	$ 3,709,346	$ 185,467	0.245	14
		Fortescue	105	34	$ 1,500,356	$ 75,018	0.702	1
		Hamersley	101	36	$ 2,767,051	$ 138,353	0.365	4
		Roebourne	93	38	$ 1,469,680	$ 73,484	0.632	2
2	Domestic herbivore management	Chichester	157	27	$ 9,786,552	$ 489,328	0.161	24
		Fortescue	146	30	$ 3,656,195	$ 182,810	0.399	3
		Hamersley	158	26	$ 6,039,934	$ 301,997	0.261	11
		Roebourne	167	24	$ 4,626,662	$ 231,333	0.361	5
3	Combined feral ungulate and domestic herbivore management	Chichester	189	19	$ 12,535,598	$ 626,780	0.151	26
		Fortescue	171	21	$ 4,932,788	$ 246,639	0.346	6
		Hamersley	204	17	$ 7,238,338	$ 361,917	0.282	9
		Roebourne	170	22	$ 5,882,806	$ 294,140	0.290	8
4	Fire management	Chichester	204	16	$ 21,862,691	$ 1,093,135	0.093	32
		Fortescue	157	28	$ 8,786,174	$ 439,309	0.178	21
		Hamersley	219	14	$ 19,381,550	$ 969,078	0.113	28
		Roebourne	199	18	$ 8,776,250	$ 438,812	0.227	16
5	Fire management and research	Chichester	255	11	$ 26,629,230	$ 1,331,462	0.096	31
		Fortescue	171	20	$ 8,786,174	$ 439,309	0.195	19
		Hamersley	293	10	$ 19,381,550	$ 969,078	0.151	25
		Roebourne	216	15	$ 8,776,250	$ 438,812	0.246	13
6	Combined feral ungulate, domestic herbivore and fire management	Chichester	378	4	$ 39,164,828	$ 1,958,241	0.096	30
		Fortescue	298	9	$ 13,718,962	$ 685,948	0.217	17
		Hamersley	444	3	$ 26,619,888	$ 1,330,994	0.167	23
		Roebourne	352	6	$ 14,659,056	$ 732,953	0.240	15
7	Cat management	Chichester	81	41	$ 4,185,148	$ 209,257	0.194	20
		Fortescue	77	42	$ 3,679,056	$ 183,953	0.210	18
		Hamersley	104	35	$ 3,969,263	$ 198,463	0.262	10
		Roebourne	120	32	$ 3,672,028	$ 183,601	0.327	7

PHOTO BELOW *Snappy gum (Eucalyptus leucophloia) with its white trunks and grey-green foliage is an iconic Pilbara species that grows across the entire Pilbara region, especially on rocky slopes and rolling hills in the Chichester subregion, especially along Snappy Gum Drive in Millstream Chichester National Park.*
PHOTO BY *Steve Dillon, DPaW.*

STRATEGY NUMBER	STRATEGY	SUBREGION	EXPECTED BENEFIT 20 YEARS	RANK EXPECTED BENEFIT	EXPECTED COST 20 YEARS	AVERAGE EXPECTED COST/YEAR	COST-EFFECTIVENESS SCORE	CE RANK (ACROSS ALL SUBREGIONS)
8	Cat management and research	Chichester	126	31	$ 39,298,862	$ 1,964,943	0.032	51
		Fortescue	109	33	$ 38,792,771	$ 1,939,639	0.028	55
		Hamersley	146	29	$ 39,082,977	$ 1,954,149	0.037	48
		Roebourne	163	25	$ 38,785,743	$ 1,939,287	0.042	46
10	Cane toad research and biosecurity	Chichester	29	54	$ 18,222,557	$ 911,128	0.016	63
		Fortescue	25	58	$ 18,222,557	$ 911,128	0.014	64
		Hamersley	38	52	$ 18,222,557	$ 911,128	0.021	60
		Roebourne	33	53	$ 18,222,557	$ 911,128	0.018	62
11	Weed management around key assets	Chichester	47	50	$ 10,570,071	$ 528,504	0.045	43
		Fortescue	53	48	$ 10,570,071	$ 528,504	0.050	41
		Hamersley	65	45	$ 10,570,071	$ 528,504	0.061	39
		Roebourne	47	51	$ 10,570,071	$ 528,504	0.045	44
12	Weed biosecurity team	Chichester	26	56	$ 9,426,114	$ 471,306	0.027	56
		Fortescue	23	60	$ 9,426,114	$ 471,306	0.024	59
		Hamersley	24	59	$ 9,426,114	$ 471,306	0.025	57
		Roebourne	18	63	$ 9,426,114	$ 471,306	0.019	61
13	Targeted exotic pasture grasses management	Chichester	21	62	$ 3,279,738	$ 163,987	0.065	38
		Fortescue	22	61	$ 3,279,738	$ 163,987	0.069	37
		Hamersley	25	57	$ 3,279,738	$ 163,987	0.076	36
		Roebourne	28	55	$ 3,279,738	$ 163,987	0.084	35
14	Combined weed and pasture grasses strategy	Chichester	85	40	$ 23,275,924	$ 1,163,796	0.036	49
		Fortescue	66	44	$ 23,275,924	$ 1,163,796	0.028	54
		Hamersley	100	37	$ 23,275,924	$ 1,163,796	0.043	45
		Roebourne	67	43	$ 23,275,924	$ 1,163,796	0.029	53
15	Hydrology management	Chichester	52	49	$ 6,043,389	$ 302,169	0.085	34
		Fortescue	54	47	$ 6,043,389	$ 302,169	0.089	33
		Hamersley	58	46	$ 6,043,389	$ 302,169	0.097	29
		Roebourne	15	64	$ 6,043,389	$ 302,169	0.025	58

PHOTO BELOW The flowers of the Hamersley peppercress (Lepidium catapycnon), a species listed as Declared Rare Flora in Western Australia and considered Vulnerable under the Environment Protection and Biodiversity Conservation Act 1999 (Cwlth) (EPBC Act). This plant is endemic to the Pilbara. PHOTO BY Darren Brearley, Onshore Environmental Consulting.

STRATEGY NUMBER	STRATEGY	SUBREGION	EXPECTED BENEFIT 20 YEARS	RANK EXPECTED BENEFIT	EXPECTED COST 20 YEARS	AVERAGE EXPECTED COST/YEAR	COST-EFFECTIVENESS SCORE	CE RANK (ACROSS ALL SUBREGIONS)
16	Habitat identification, protection and restoration	Chichester	224	13	$ 37,949,856	$ 1,897,493	0.059	40
		Fortescue	167	23	$ 9,614,197	$ 480,710	0.174	22
		Hamersley	327	7	$ 25,862,639	$ 1,293,132	0.126	27
		Roebourne	234	12	$ 9,220,706	$ 461,035	0.254	12
17	Total combined strategy	Chichester	445	2	$ 145,732,859	$ 7,286,643	0.031	52
		Fortescue	325	8	$ 91,445,242	$ 4,572,262	0.036	50
		Hamersley	592	1	$ 120,884,817	$ 6,044,241	0.049	42
		Roebourne	376	5	$ 91,984,817	$ 4,599,241	0.041	47

PHOTO BELOW A flock of Plumed Whistling-duck (Dendrocygna eytoni) taking flight from a native soak on the Fortescue Marsh.
PHOTO BY Hamish Robertson, DPaW.

4.2 STRATEGIES REQUIRED TO AVOID LOSSES AND SECURE BIODIVERSITY

Without implementation of the threat management strategies assessed in this report, 13 of the 53 threatened species (25% of species analysed) are at a high risk of functional loss (probability of persistence <0.5) in the Pilbara over the next 20 years.

However all of these probable extinctions are potentially avoidable—if the proposed management strategies are implemented then our experts predicted that all species could be protected to a level where the probability of persistence was greater than 50% (*Table 3* and *Table A4*). The vertebrate species most at risk are small to medium weight range mammals and birds such as the greater bilby, spectacled hare-wallaby, black-flanked rock wallaby, pale field rat and the night parrot. Many of these species are wide ranging and are threatened elsewhere across their range (Carwardine *et al*. 2012). All of these species are known to be particularly threatened by cat and fox predation and alteration of vegetation structure and condition. The plant species that are most at risk are predominantly small herbaceous shrubs and herbs, including: Coondiner myriocephalus, Coondewanna vittadinia, *Teucrium pilbaranum*, De Grey saltbush, Muccan fuchsia, and Hamersley tetratheca. Two trees also have a risk of extinction greater than 50% if no action is taken—the Hamersley wilga and O'Meara's minni ritchi.

Our complementarity-based approach releaved that the amount of funding available for conservation has a direct influence on the number of species that are likely to be protected above a threshold persistence level, assuming funds are allocated optimally for conserving these significant species (*Figure 3*).

When aiming to achieve persistence thresholds for all species to above 90%, cat management was the best option to take with a budget of less than $0.5m/year, securing Gane's blindsnake for an estimated $0.38m/year (*Table A6*). Fire management and research allowed securing two species—Gane's blindsnake and mountain thryptomene—with a slightly larger budget of $2.68/year. Amongst all possible combinations of strategies, the strategy that maximises the number of species above 90% threshold was the combined feral ungulate, domestic herbivore and fire management for $4.17m/year and a total of seven species secured above 90% persistence threshold (the two secured by the baseline, the two secured above, plus Hamersley peppercress, bush stone-curlew and Pilbara barking gecko). All other species were not able to reach the 90% persistence threshold even if additional strategies were implemented.

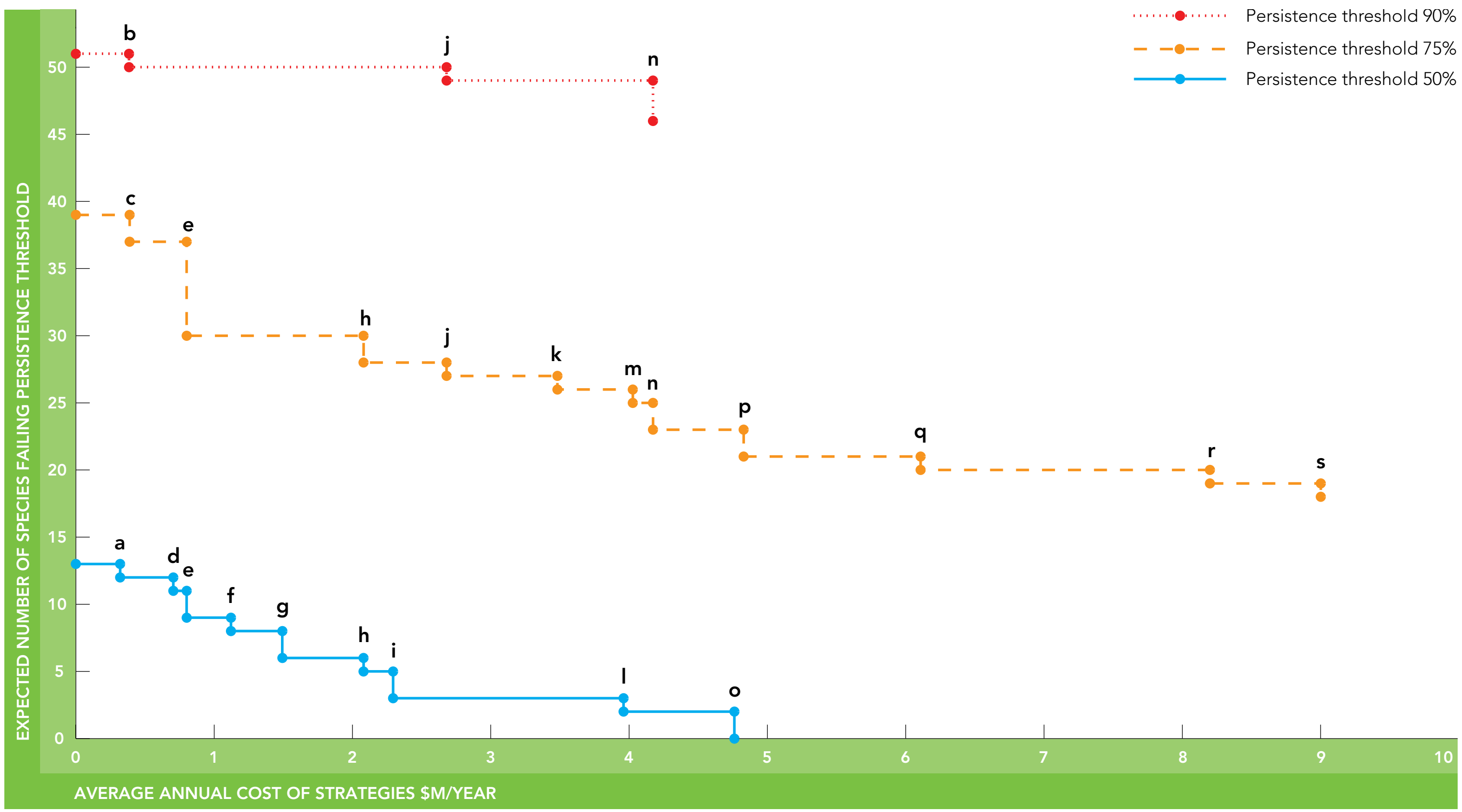
When considering a lower persistence threshold of 75%, feral ungulate management was the strategy that secured the maximum amount of species for less than $0.5m/year ($0.39m/year) with a total of 16 species secured above 75% (bush stone-curlew and four-chained slider). The highest allocation of funding recommended was the group of strategies 'combined feral ungulate, domestic herbivore and fire management, sanctuaries and habitat identification, protection and restoration' ($9m/year). This group of strategies secured 35 species above 75% with sanctuaries contributing to secure the spectacled hare-wallaby (*Table A5*).

If a species is deemed secure when the probability of persistence is greater than 0.5, then all species can be secured by implementing three management strategies: domestic herbivore management, fire management and research, and sanctuaries with an annual estimated cost of $4.76m (*Figure 3*). Sanctuaries were the cheapest strategy to secure the black-flanked rock wallaby and pale field-rat (*Table A4*).

While *Figure 3* provides insight into which combinations of strategies are 'optimal' for the two objectives maximising the number of species above a given persistence threshold and minimizing cost, it is important to realize that the definition of a 'secure' species drives the results. Strategies with no apparent benefit on the plot may incrementally benefit many species, but fail to push their probability of persistence above the arbitrary persistence threshold. Strategies that are not selected in *Figure 3* may have very similar total benefits. The fact that a strategy is not selected in *Figure 3* does not necessarily mean that strategy is a poor investment. Despite these caveats, *Figure 3* does illustrate that there exists a combination of strategies that protects high numbers of species per dollar spent given a persistence threshold.

Figure 3 The number of species that are not likely to be protected at three persistence thresholds for different investment levels spent optimally and effectively on targeted threat management.

The baseline scenario secures only two species at a persistence threshold of 90% or more, meaning that 51 species fail to meet that threshold. At lower persistence thresholds, 75% and 50% fewer species fail to meet each threshold (39 and 13 species, respectively). If managers or decision makers require a 50% chance of species persistence over 20 years, then all species may be secured by implementing domestic herbivore management, sanctuaries and fire management and research with an investment of roughly $4.76m/year. If the required threshold is set to 90% chance of persistence over 20 years, then only seven species can be secured regardless of the level of investment. Additional spending may raise persistence of unsecured species, but it does not raise persistence above the threshold.



- **a** Hydrology management
- **b** Cat management
- **c** Feral ungulate management
- **d** Cat and Hydrology management
- **e** Sanctuaries
- **f** Sanctuaries and Hydrology
- **g** Combined feral ungulate and domestic herbivore
- **h** Domestic herbivore and Sanctuaries
- **i** Combined feral ungulate and domestic herbivore and Sanctuaries
- **j** Fire management and research
- **k** Fire management and research and Sanctuaries
- **l** Domestic herbivore and Fire management and research
- **m** Habitat identification, protection and restoration
- **n** Combined feral ungulate, domestic herbivore and fire management
- **o** Domestic herbivore and Fire management and research and Sanctuaries
- **p** Sanctuaries and Habitat identification, protection and restoration
- **q** Domestic herbivore and Sanctuaries and Habitat identification, protection and restoration
- **r** Combined feral ungulate, domestic herbivore and fire and Habitat identification, protection and restoration
- **s** Combined feral ungulate, domestic herbivore and fire and Habitat identification, protection and restoration and Sanctuaries

PHOTO BELOW A Pilbara Olive Python (Liasis olivaceus barroni) out foraging at the night through a rock pile in the Pistol Ranges on the Burrup Peninsula. This python was regularly tracked over a 40 months period by members of the Nickol Bay Naturalist's Club with support from DPaW and the National Heritage Trust.
PHOTO BY Michael Tutt, Nickol Bay Naturalists' Club, Karratha.

Table 3 Species list indicating the species that are likely to be lost or secured without any strategies and with all strategies implemented.

SPECIES NAME	WITHOUT STRATEGIES (EXPECTED PROBABILITY OF PERSISTENCE IN %)				WITH BEST STRATEGIES IMPLEMENTED (EXPECTED PROBABILITY OF PERSISTENCE IN %)			
	LIKELY LOST FROM REGION (<50)	50–75	75–90	LIKELY SECURED IN REGION (>90)	LIKELY LOST FROM REGION (<50)	50–75	75–90	LIKELY SECURED IN REGION (>90)
FLORA								
Mardie fanflower		✓					✓	
Hamersley peppercress			✓					✓
Coondiner myriocephalus	✓					✓		
Coondewanna vittadinia	✓					✓		
Teucrium pilbaranum	✓					✓		
Hamersley minni ritchi		✓					✓	
Mosquito creek wattle		✓					✓	
Abydos wattle			✓				✓	
Witarra		✓					✓	
Paraburdoo heath		✓				✓		
De Grey saltbush	✓					✓		
Muccan fuchsia	✓					✓		
Hamersley wilga	✓						✓	
Channar hibiscus		✓					✓	
Oakover peppercress		✓					✓	
Pilbara trudgenii			✓				✓	
Strelley foxglove		✓					✓	
Brockman mulla-mulla		✓					✓	
Hamersley tetratheca	✓						✓	
Mountain thryptomene			✓					✓
O'Meara's minni ritchi	✓						✓	
Millstream fan-palm			✓				✓	

SPECIES NAME	WITHOUT STRATEGIES (EXPECTED PROBABILITY OF PERSISTENCE IN %)				WITH BEST STRATEGIES IMPLEMENTED (EXPECTED PROBABILITY OF PERSISTENCE IN %)			
	LIKELY LOST FROM REGION (<50)	50–75	75–90	LIKELY SECURED IN REGION (>90)	LIKELY LOST FROM REGION (<50)	50–75	75–90	LIKELY SECURED IN REGION (>90)
TERRESTRIAL VERTEBRATES								
Star finch			✓				✓	
Night parrot	✓					✓		
Bush stone-curlew		✓						✓
Fortescue grunter		✓				✓		
Greater bilby	✓					✓		
Ghost bat		✓				✓		
Little north-western freetail bat			✓				✓	
Pilbara leaf-nosed bat		✓				✓		
Long-tailed dunnart		✓				✓	✓	
Spectacled hare-wallaby	✓					✓		
Black-flanked rock-wallaby	✓					✓		
Rothschild's rock-wallaby		✓				✓		
Mulgara		✓					✓	
Northern quoll		✓					✓	
Lakeland Downs mouse		✓					✓	
Western pebble-mound mouse			✓				✓	
Pale field-rat	✓					✓		
Pilbara barking gecko		✓						✓
Airlie Island ctenotus		✓				✓		
Cape Lambert slider		✓				✓		
Four-chained slider		✓					✓	
Lined soil crevice skink		✓					✓	
Pilbara olive python				✓				✓
Gane's blindsnake			✓					✓

PHOTO BELOW *Iron-rich banded iron breakaways and scree slopes above Bungaroo Creek in the western Hamersley Range, south of Pannawonica.*
PHOTO BY *Stephen van Leeuwen, DPaW.*

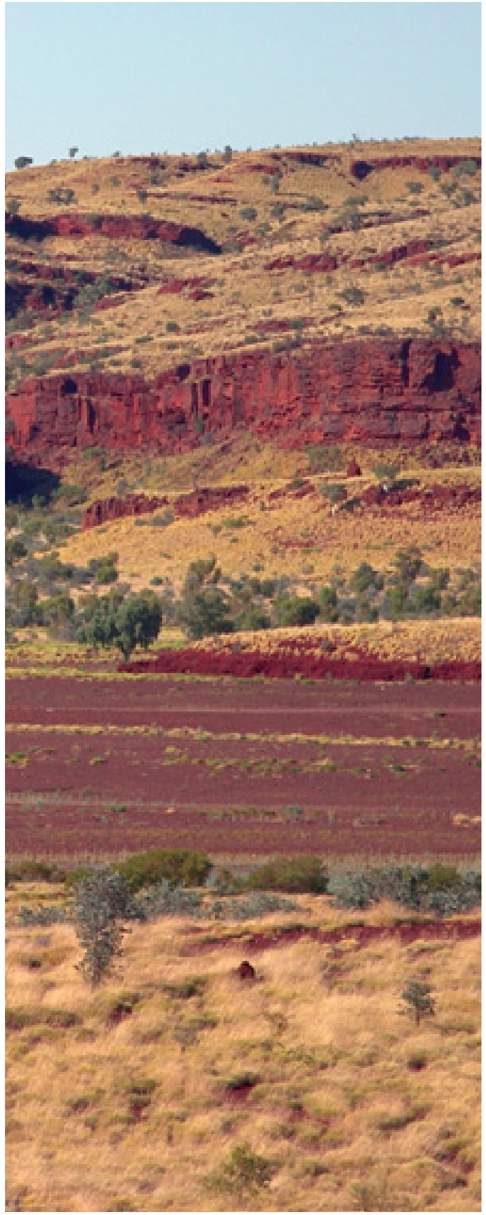


PHOTO BELOW A granitic dome rising from the spinifex dominated (Triodia spp.) sandplain in the south western corner of Cane River Conservation Park in the Roebourne subregion.
PHOTO BY Steve Dillon, DPaW.

SPECIES NAME	WITHOUT STRATEGIES (EXPECTED PROBABILITY OF PERSISTENCE IN %)				WITH BEST STRATEGIES IMPLEMENTED (EXPECTED PROBABILITY OF PERSISTENCE IN %)			
	LIKELY LOST FROM REGION (<50)	50–75	75–90	LIKELY SECURED IN REGION (>90)	LIKELY LOST FROM REGION (<50)	50–75	75–90	LIKELY SECURED IN REGION (>90)
TERRESTRIAL INVERTEBRATES								
Dupuch land snail			✓				✓	
SUBTERRANEAN								
Middle Robe draculoides			✓				✓	
Mesa A paradraculoides		✓					✓	
Mesa B paradraculoides				✓				✓
Mesa G paradraculoides		✓					✓	
Mesa K paradraculoides		✓					✓	
Blind cave eel			✓				✓	
TOTAL SPECIES	**13**	**26**	**12**	**2**	**0**	**18**	**28**	**7**

PHOTO LEFT The Greater Bilby (Macrotis lagotis) has a scattered disjunct distribution across the Chichester, Fortescue and Hamersley subregions. It has a preference for sandier soils in habitats with a low and open Acacia shrub overstorey. It is frequently found along the alluvial washes of the larger river systems.
PHOTO BY Kanyana Wildlife Rehabilitation Centre (Inc).

PHOTO RIGHT Ghost Bat (Macroderma gigas).
PHOTO BY Henry Cook, Rapallo.

4.3 CO-BENEFITS OF CONSERVATION MANAGEMENT STRATEGIES

Conservation management strategies in the Pilbara have the potential to contribute to a range of benefits other than our metric of improved persistence of threatened flora and fauna.

Other important conservation objectives in the Pilbara include the protection of short-range endemics, other invertebrates, arid tropical mangroves (Environmental Protection Authority 2001) and the integrity of other plant communities, as well as the protection of native flora and fauna that are not currently listed as threatened. Some related objectives contribute to achieving many of the Pilbara Development Commission 2010–2013 goals and objectives including more sustainable mining, tourism and pastoral activities, the three top industries within the region (Department of Regional Development and Lands 2011). Increasing evidence has shown that reducing threats to the integrity of native ecosystems can have added benefits for key ecosystem services including carbon sequestration, drought tolerance, water quality, hydrological flows (Isbell *et al.* 2011), and resilience to changing perturbations such as the ability of plant communities to recover after fire (MacDougall *et al.* 2013) and increasing climate variability.

Another major benefit is meeting the conservation and land management goals of Traditional Owners in the Pilbara. Traditional Owners are key stakeholders comprising more than 16% of the regional population within the Pilbara (Department of Regional Development and Lands 2011). The actions identified within each strategy may also provide increased opportunities for Indigenous engagement and employment.

We describe in more detail some of the co-benefits and potential negative interactions for each strategy over page (*Table 4*).

PHOTO BELOW Northern Quoll (Dasyurus hallucatus) at Red Hill Homestead.
PHOTO BY Leanne Corker, Red Hill Station.

Table 4 Potential co-benefits of proposed strategies.

Where strategies address a similar threat (e.g. feral ungulates and introduced herbivores) they have been grouped together for the purposes of explaining co-benefits.

STRATEGY	POTENTIAL CO-BENEFITS (+) AND NEGATIVE INTERACTIONS (–)
Combined feral ungulate and domestic herbivore management	+ Employment opportunities in feral herbivore control and unmanaged stock management + Improved vegetation community health + Improved soil health + Reduced disturbance to vegetation and fewer weed invasions + Improved water quality + Potential increases in carbon sequestration and storage + Removal of feral herbivores may provide increased productivity for domestic stock and reduce disease risk – Removal of domestic stock could negatively affect pastoralists through loss of productivity
Fire management and research	+ Net reduction in carbon dioxide emissions over the landscape + Potential employment opportunities for local communities, including Traditional Owners and pastoralists + Effective fire management can decrease the spread of fire-tolerant weeds (e.g. buffel and gamba grass) + Less disruption to supply of services such as, road transport, water and power/electricity both for residential and industrial/mining users + Less damage to crucial infrastructure associated with communications and railway operations + Greater security and low risk to remote facilities such as exploration camps and mining villages + Improved pasture management
Predator control strategies: cat management and research; sanctuaries; cane toad research and biosecurity	+ Creation of employment opportunities in the Pilbara and research positions within and outside the region + Reduced effects of cat and toad predation on non-threatened species + Sanctuaries may provide economic benefits by providing a sustainable tourism asset – Potential for baiting to kill domestic cats (and domestic dogs) if improperly applied near settlements – Some inconvenience caused through biosecurity checks on major transport pathways – Non-target impacts of predator management on native fauna, e.g. raptor secondary poisoning due to ingestion of poisoned animals

PHOTO BELOW *The Millstream fan-palm (Livistona alfredii) on Caves Creek in the Hamersley subregion. This fan-palm is restricted to calcrete soils adjacent to a few permanent wetlands in the Chichester and Hamersley subregions of the Pilbara. It is not quite endemic to the Pilbara as two plants are known from Cape Range in the Southern Carnarvon Basin.*
PHOTO BY Stephen van Leeuwen, DPaW.

STRATEGY	POTENTIAL CO-BENEFITS (+) AND NEGATIVE INTERACTIONS (–)
Combined weed and pasture grasses strategy	+ Increased persistence of native plants + Improved soil health + Improved water quality + Weed control can improve pastoral productivity in some instances + Creation of employment: program manager, Indigenous rangers, coordinator and GIS specialist + Early detection of weeds by the biosecurity team could prevent enormous costs of eradicating weeds in the future + Potential to reduce list of species likely to be selected and grown on irrigated pastures (for fodder or biofuels) as many of these species are major environmental weeds – Control of exotic pasture grasses around key conservation assets may negatively affect pastoralists through loss of productivity
Hydrology management	+ Ensure long-term health of wetlands of national significance, waterways, aquifers, estuaries and floodplains + Protection of migratory bird breeding habitat on the Fortescue Marsh + Sustainability of existing major tourist assets including the Millstream wetlands in the Millstream Chichester National Park + Preserve the largely undocumented stygofauna community of the Pilbara, which contains many undescribed species + Sustained surface and groundwater quantity and quality + Maintain vegetation communities reliant on groundwater table + Understanding the role of groundwater will benefit the mining industry, which requires sustained large volumes of groundwater for dust suppression and mineral processing, as well as carrying out dewatering
Habitat identification, protection and restoration	+ Representative reserves and restoration will protect non-threatened native species

PHOTO BELOW Fortescue Falls, Dales Gorge in Karijini National Park.
PHOTO BY Steve Dillon, DPaW.

4.4 OTHER IMPORTANT ENABLING ACTIVITIES

During the process of the workshop a number of additional activities were identified that could not be analysed in terms of cost-effectiveness but that are considered important for the successful delivery of the strategies analysed.

These include knowledge sharing, adaptive management programs for implementation, monitoring and evaluation and stakeholder engagement and community awareness.

4.4.1 KNOWLEDGE SHARING

One of the recurring themes of the workshop was the need for knowledge sharing amongst the many stakeholders working in the Pilbara. Despite a Pilbara-wide regional biological survey conducted from 2002 to 2012 (McKenzie *et al.* 2009), the biota of the Pilbara is still considered poorly known, as exemplified by the numbers of novel plants and animal being discovered on a regular basis and the explosion in the richness of subterranean fauna, particularly stygofauna which has increased from about 40 species in 2002 to over 350 species in 2007 (Halse *et al.* 2014) with modelled estimates of between 500–550 species (Eberhard *et al.* 2009) now considered substantially conservative (Guzik *et al.* 2010).

This lack of knowledge hinders management effectiveness in delivering biodiversity results. With the rapid expansion in exploration and development of the Pilbara, vast numbers of ecological surveys and research projects are being commissioned to generate a valuable data set of the distributions of the threatened species of the Pilbara.

However participants at the workshop emphasized that most of the data generated are not accessible and there is a need to collate this information and make it publicly available. For example, prior to 2005, over 800 biological survey reports had been undertaken for parts of the region, yet only two broad-scale biological studies were available (McKenzie *et al.* 2009). This has been partially addressed by the Pilbara Biological Survey and initiatives such as NatureMap (Department of Environment and Conservation 2007) and the Atlas of Living Australia (ALA 2010), however much survey data remains inaccessible, either in unpublished or privately-held databases.

For example, BHP Billiton, one of the largest iron ore miners in the bioregion, have conducted over 350 environmental studies in the region over the past decade (BHP Billiton 2013). Other companies, government agencies and environmental consultancies are likely to have similar databases that could be combined to greatly increase our understanding of the Pilbara's biota. Data sharing would improve knowledge of species ranges and critical habitats as well as expected impacts of development, and could be used to design more effective and targeted management strategies. This could potentially reduce the cost of some management actions by focusing management in areas where target species are present.

Implementation of the strategies identified in the report requires knowledge of range sizes and critical habitat of threatened species, as well as improved knowledge of species' requirements and responses to threats. While uncertainty should not prevent action being taken to prevent species decline, participants agreed that a minimum level of research is needed for effective action. One key research project identified by the group would be to collate the existing information and create maps of key assets for the listed threatened species to enable targeted management. This would be challenging for some species (e.g. stygofauna), but for others (e.g. critical weight range mammals), much of the data already exists.[1] Combined with data sharing, this comparatively straightforward project could potentially result in large improvements in conservation efficacy.

4.4.2 ADAPTIVE MANAGEMENT TO ADDRESS UNCERTAINTY

A further essential consideration is the establishment of a monitoring program to report the status of threatened species and allow for adaptive management.

Adaptive management or learning by doing is recognised as a key principle to modern conservation programmes, where management actions are monitored and strategically altered based on the uncertainty that is reduced as the system becomes better understood (Walters and Hilborn 1978, McCarthy and Possingham 2007). Adaptive management was identified as an essential part of all management strategies elicited in this study. Participants acknowledged that there are many uncertainties in current and future conditions for undertaking conservation actions in the Pilbara. Current uncertainties include the benefits of implemented strategies to the species of the Pilbara. An adaptive management approach will allow managers to improve the efficiency of implemented strategies and update key estimates such as the benefits to the species and implementation costs as data is collected over time. Future uncertainty such as altered climate conditions and consequences to the conservation significant species of the Pilbara can also be accounted for in an adaptive management framework. Recent advances have shown that adaptive management programs can be devised in a cost-effective manner. Notably, recent studies have demonstrated how managers can choose robust conservation actions that anticipate the consequences of changing environmental conditions (McCarthy and Possingham 2007, Nicol *et al.* 2013).

4.4.3 STAKEHOLDER ENGAGEMENT

Stakeholder engagement and general community awareness is essential for successful delivery of the management strategies presented in this report.

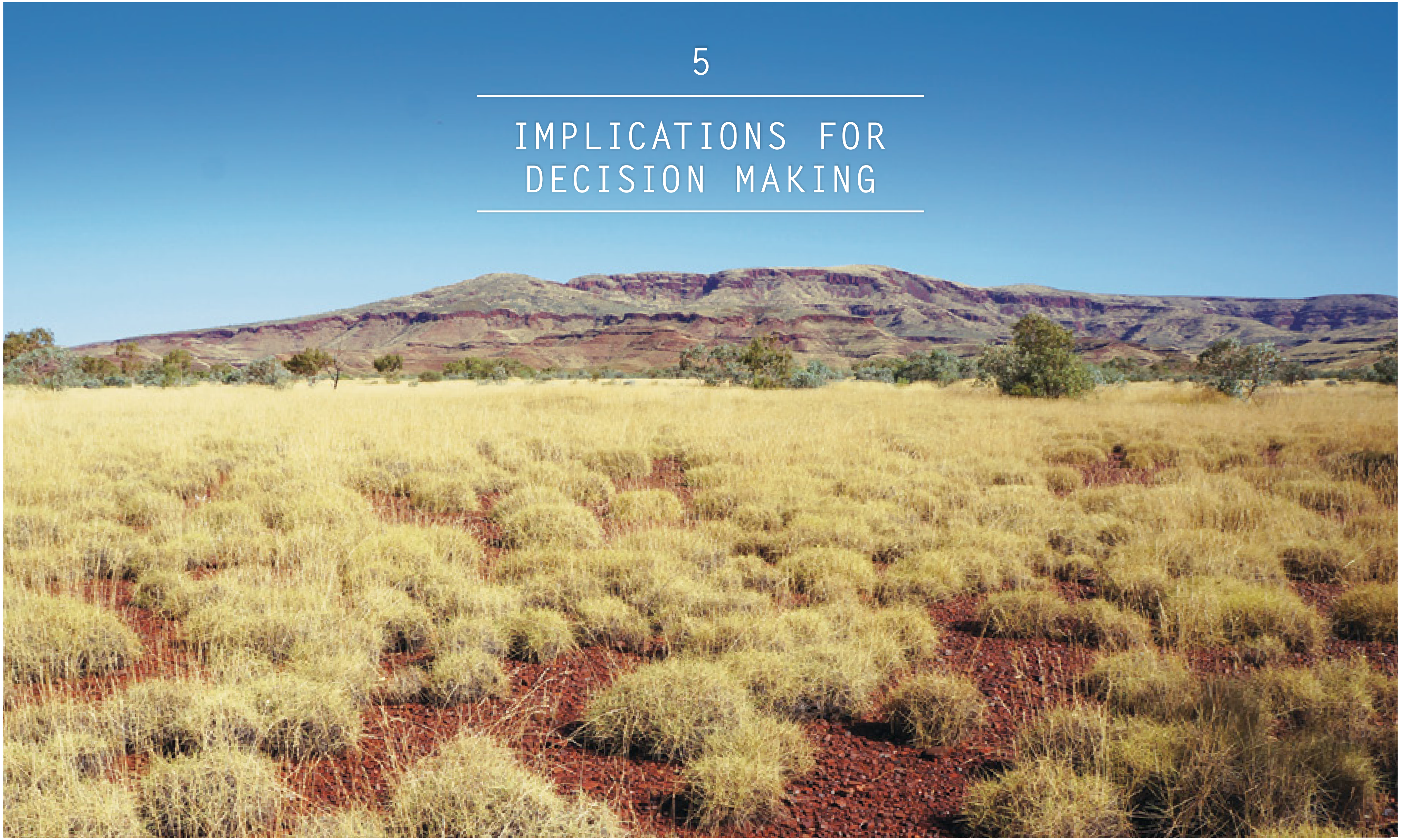
A discussion at the workshop identified stakeholders at various levels, from high level decision makers (politicians and their advisors), to those directly responsible for looking after country, including park rangers, land holders, managers and Traditional Owners. Support at all levels is ideal for successful conservation outcomes.

The community at large has an important role to play in the conservation of Pilbara biodiversity, as the ultimate 'end-users' of the biodiversity values conserved. Any strategies that are implemented should be planned for in consultation with relevant community stakeholders (including pastoralists, mining companies and Indigenous communities) to maximise the benefits of the strategies and ensure they are implemented appropriately. The role of workshop participants in supporting and raising awareness of the approach and its results was also identified at the workshop.

PHOTO BELOW Distortion of the bedding in the banned iron formation is clearly evident in the cliff face below spar pool at Hamersley Gorge in Karijini National Park. PHOTO BY Stephen van Leeuwen, DPaW.

[1] *A series of Threatened species workshops were convened in 2013 to address this issue. Interested readers can refer to the workshop outputs and to the Pilbara Threatened Fauna theme in NatureMap at http://naturemap.dpaw.wa.gov.au/threatenedfauna*

PHOTO BELOW Spinifex grassland with emergent mallee (Eucalyptus gamophylla) and bloodwoods (Corymbia deserticola) along shallow drainage lines at the base of the Hamersley Range escarpment east of Munjina.
PHOTO BY Jeff Pinder, DPaW.



5

IMPLICATIONS FOR DECISION MAKING

PHOTO BELOW Basalt boulder field, north of Mt Herbert, Millstream Chichester National Park.
PHOTO BY Steve Dillon, DPaW.

5.1 USING THE INFORMATION IN THIS REPORT

The information we present in this report is designed to help guide investment for improving the conservation of threatened species in the Pilbara. For the first time in the Pilbara region, we have gathered a comprehensive set of information on the costs of maintaining functional populations of threatened species by abating a key set of threats (identified by stakeholders) through land management actions.

Our prioritisation of conservation actions for the region is presented as a guide only. We do not aim to address the cultural, socio-economic or spatial components necessary for an implementation plan, although we do identify some key practicalities necessary to realise the broader strategies.

We also did not consider the effectiveness of current nor future management delivery models, although this is a crucial component of successful conservation management. Cost-effectiveness depends on the objectives used; in our case the objective is the improved persistence of threatened native flora and fauna. We acknowledge that with the consideration of other factors, the priorities may change and some strategies may not be appropriate in certain locations.

Some of the necessary funds for conserving flora and fauna already exist as part of current projects, such as the Pilbara Corridors Project (Department of Environment, Biodiversity Fund and Rangelands WA NRM, and Conservation Systematics of Western Pilbara (Western Australia Museum)). Our results suggest that additional investments are however, necessary to combat existing and emerging threats to the endangered, threatened and vulnerable flora and fauna. Future conservation activities should build upon and enhance effective existing initiatives, both for reasons of economic efficiency and to ensure that the invaluable knowledge and experience held by existing managers and decision makers is not lost. The cost-effectiveness of actions for achieving improved persistence of wildlife and other benefits will vary depending upon the values of the stakeholders, planners, implementing agents and broader objectives for the region.

The strategies we cost do not include expenses such as the financial and opportunity costs of changing land tenure to protected areas nor establishing offset management areas. Expanding the protected area network in the Pilbara may have the potential to increase the feasibility of implementing some management strategies and therefore improve the chances of successfully protecting biodiversity. Indigenous Protected Areas (IPA) could play an increasing role in securing areas for conservation and enabling suitable management as well as involving the skills and knowledge of Traditional Owners. Opportunities do exist for the dedication of IPA's where exclusive possession Native Title ownership has been determined which in the Pilbara bioregion will primarily be over existing Aboriginal reserve lands. Regardless of how much of the Pilbara is dedicated to protected areas, effective management both within and outside these

*PHOTO BELOW Mulga (*Acacia aneura *sens. lat.) woodland with herbaceous understorey of* Goodenia prostrata *and* Brachyscome ciliaris *on Wunna Munna Flats, west of Newman.*
PHOTO BY Stephen van Leeuwen, DPAW.

areas is required for addressing species declines. Declines in species recorded in the many existing protected areas across northern Australia indicate the importance of management across all land tenure types (Woinarski *et al*. 2010; Woinarski *et al*. 2011).

As identified within the strategies developed by key stakeholders of the Pilbara, there is a great deal of additional work that would assist effective and responsive conservation management of the Pilbara region. This is evidenced by the consistent identification of the need to fund more research as part of most strategies (*Appendix 1*, *Table A2*). However, it will take substantial amounts of time to complete tasks such as a comprehensive scientific study of the responses of species to threats and actions. Rapid implementation of any undisputed and 'no regret' conservation strategies in the meantime are necessary to avoid imminent declines.

Since uncertainty usually exists about the impact of many actions (e.g. hydrology management) or the efficacy of others (e.g. feral cat control actions), an adaptive management framework is essential (Walters and Hilborn 1978, Westgate *et al*. 2013).

A well-coordinated implementation strategy will also increase the likelihood of producing broader benefits and opportunities arising from carrying out the various conservation actions, which includes working with a variety of stakeholders to develop the plan and monitor its efficacy. Finally, the actions within each strategy must be effective, otherwise the probability of success will decrease, the costs of delivery will increase, or both.

SOME AREAS OF ADDITIONAL WORK RECOMMENDED INCLUDE:

- Support ongoing negotiation processes with major landholder groups, particularly Traditional Owners and pastoralists, about their conservation and land management goals.
- Further effort to identify key actions and benefits for coastal mangroves.
- Further effort to predict the scale of future potential threats and how to minimise these (e.g. irrigated agricultural expansion, mining, climate change).
- Integration of this work with the trans-boundary issues of the coastal systems, specifically the inshore marine waters, islands/coastlines with associated intertidal habitats and the freshwater inputs, as well as with marine conservation priorities.
- Consideration of this work in the context of actions occurring in the adjacent bioregions such as the Kimberley, a region that has also underdone a cost-effectiveness assessment (Carwardine *et al*. 2011, 2012).
- Integration of this work with cultural and socio-economic considerations. This step will be a critical component of successful conservation in the Pilbara.
- Research to determine the more effective and efficient delivery models for each management action.
- Designing an implementation strategy in collaboration with stakeholders.
- Developing an adaptive management framework to inform data collection and evaluate management actions.
- Support for ongoing research designed and delivered via an adaptive management framework, into the ecology/biology of the

53 conservation significant species cited and how they are impacted by the current threats and the potential responses to the mitigation strategies identified.

- Support for the development of protocol, procedures and facilities (e.g. NatureMap) to capture biological and species survey data from the Pilbara which is made available to all stakeholders via a suite of free tools and applications.

5.2 CAVEATS

It was necessary to make a range of assumptions and generalisations for this analysis. These include:

- The limited information on the extent of each ecosystem type within each bioregion, as well as information on wildlife populations within each ecosystem type, meant our analyses were conducted at a coarse level of IBRA subregions.
- Since costs of some actions within strategies were scaled to the area of subregions and benefits were not, our subregional analysis may favour smaller subregions. Accuracy could be increased with improved information on species distributions and treatment area for actions within subregions. For example, sanctuaries operate over a smaller area than other strategies considered and therefore may have obtained a lower cost-effectiveness rank if the size of the treatment area was considered.
- Most of the data used in this analysis were based on the knowledge of experts and stakeholders, which may or may not include beliefs formed on the basis of published, peer-reviewed scientific research.
- For many of the conservation actions, costs were uncertain and real costs may prove to be higher or lower than predicted.
- The cost-effectiveness ranks of strategies do not consider the species benefited by the strategies ranked above them. This enabled each strategy to be given an independent rank. However, a strategy that conserves a species that has not yet been conserved may be more cost-effective than a strategy which conserves a species that has already been protected in another region, all else being equal.
- Interactions between threats could not be comprehensively addressed, although they were considered to some extent by the many combined strategies evaluated by the experts as part of this project. For the complementarity analysis we assumed that strategies act independently on species, when in reality a combination of strategies may have a combined benefit that is more or less than the benefits of each strategy estimated in isolation.
- We assumed actions could be funded or not funded, but in reality actions may be partially funded and there may be relationships between cost-effectiveness and increased funds to up-scale management intervention (as more funds are put into a strategy, the probability of success and likely benefits of the strategy may also increase, which may change the cost-effectiveness ranking).
- There are many uncertainties in future conditions for undertaking conservation strategies in the Pilbara, such as the consequences of climate change and future developments not considered in this analysis. Uncertainties concerning climate change and future developments will likely compound the existing threats and accelerate declines. A precautionary approach suggests that we should increase investment early, monitor and review the effectiveness of strategies and be vigilant in identifying emerging threats.
- The baseline is a theoretical scenario as there is management currently occurring in some of the strategies we identify and additional strategies may be planned, however, the goal of our analyses is to demonstrate potential cost-effectiveness of strategies compared with not implementing strategies, to enable their relative values to be assessed.

PHOTO BELOW Samphire (Tecticornia spp.) shrublands on the Fortescue Marsh with the Hamersley Range escarpment in the background. PHOTO BY Steve Dillon, DPaW.

Our message explains the likely losses of threatened species faced by the Pilbara without targeted increases in investment in conservation management of the region and details the best actions for avoiding these losses.

The relative cost-effectiveness for wildlife of the actions and the relative benefits (in terms of species losses avoided) of carrying out combinations of actions are likely robust and the methods we use are explicit, systematic, knowledge-based and can be updated as improved information on the costs and benefits of conservation actions becomes available.

PHOTO BELOW Mesa and butte landforms on Cane River Conservation Park in the west of the Hamersley subregion.
PHOTO BY Steve Dillon, DPaW.

6 CONCLUDING REMARKS

*PHOTO LEFT The Spectacled-hare Wallaby (*Lagorchestes conspicillatus*) is now extremely rare in the Pilbara having not been positively recorded from the field for over 15 years. The last known extant population in the Pilbara is thought to have become locally extinct as a consequence of too frequent burning of long unburnt spinifex habitat.*
PHOTO BY Jiri Lochman, Lochman Transparencies.

*PHOTO RIGHT The Fortescue Grunter (*Leiopotherapon aheneus*) is endemic to river systems of northwestern Western Australia.*
PHOTO BY Jess Delaney, WRM Water and Environment.

This report is written at an important time for the future of the Pilbara's biodiversity. As development in the region booms, new pressures have arisen that may impact biota in negative ways. Information provided by participants at our workshop predicts that existing and new threats may cause 25% of the Pilbara's conservation significant species to become functionally extinct in the next 20 years without effective threat management.

At the same time, development brings opportunities to protect the Pilbara's biodiversity in the form of increased survey effort, public and government scrutiny and potentially increased investment in land management across the region.

To best harness this opportunity, a systematic, region-wide approach is required to determine the best management actions to implement, at a scale that is sufficient to prevent the functional loss of species across the landscape. This report is an effort to determine both which management actions are required and the level of investment required to halt declines in the Pilbara's conservation significant species.

According to our analysis, the most cost-effective strategy to protect the threatened species of the Pilbara was to manage feral ungulates through a program of coordinated aerial shooting and exclusion fencing around key conservation assets. The next most cost-effective strategy was to establish predator-free wildlife sanctuaries, while the third most cost-effective strategy was to control cat predation around key wildlife assets with an ongoing program of targeted baiting, shooting and trapping. Each of the top three ranked strategies could be implemented for an average annual estimated cost of less than $1 million/year over 20 years, and this would benefit almost all 53 species to some extent.

To give threatened species the best chance of persisting over 20 years within the limits of the analysis we present would involve implementation of all of the recommended strategies. This was estimated to cost $17.5 million/year over 20 years, primarily spent on habitat restoration, fire management and weed control. Implementing all strategies would prevent 13 species from likely functional extinction in the next 20 years, an investment of less than $1.4 million/year for each species saved from likely functional extinction. The costs included in the calculations are indicative of the direct on-ground costs for species protection, so additional funds would be required to support implementation between agencies and landholders across the region and to implement viable plans that consider factors other than biological conservation. There is also a small investment required to improve data sharing between stakeholders working in the Pilbara to ensure that conservation spending is based on the best available data to achieve maximum efficiency.

This report is designed to support decision makers by providing the first region-wide prioritisation that estimates which management strategies are the most cost-effective investments for threatened species of the Pilbara. We present an aggregation of the knowledge held by 49 experts and stakeholders on the ecology and management of the Pilbara, together with the cost data necessary to help guide decision-making. The strategies presented here can improve the chance of persistence of the threatened species of the Pilbara while also generating other benefits such as employment, more sustainable mining, pastoral and tourist industries, and improved ecosystem services such as carbon sequestration and improved soil health.

If key threats to the conservation significant species of the region are managed, the Pilbara has the potential to maintain and enhance its reputation as a region with exceptional biodiversity values in addition to exceptional mineral resources. The opportunity now exists to implement a systematic, region-wide conservation strategy to protect the threatened species of the Pilbara and conserve the biota of this unique region.

PHOTO BELOW Snappy gum (Eucalyptus leucophloia) *silhouetted by a Pilbara sunrise, McPhee Creek, East Pilbara.*
PHOTO BY Outback Ecology.

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PHOTO TOP A thicket of Parkinsonia (Parkinsonia aculeata) on the bank of the Ashburton River just south of Onslow in the Gascoyne bioregion.
PHOTO BY Linda Anderson, DAFWA.

PHOTO BOTTOM A herd of Camels at the interface between the Pilbara and the Great Sandy Desert bioregions.
PHOTO BY Linda Anderson, DAFWA.

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PHOTO BELOW Footprints in the sand—secondary dunes fringing coastal embayments and coves along the Pilbara coast support spare vegetation dominated by beach spinifex (Spinifex longifolius).
PHOTO BY Vicki Long, Astron Environmental Services.

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PHOTO BELOW Samphire (Tecticornia spp.) shrublands on the Fortescue Marsh with the Hamersley escarpment in the background. This shrubland supports several Priority-listed flora species that are endemic to the Marsh.
PHOTO BY Steve Dillon, DPaW.

APPENDICES

APPENDIX 1: METHODOLOGICAL DETAILS

SPECIES LIST

Table A1 Focal list of conservation significant flora and fauna found within each of the Pilbara IBRA subregions and their conservation status and codes

Please follow the link for a detailed description of the codes used www.dpaw.wa.gov.au/images/documents/plants-animals/threatened-species/Listings/Conservation_code_definitions_18092013.pdf

TAXON DATA			IBRA DISTRIBUTION				CONSERVATION STATUS					
CATEGORY FOR WORKSHOP	SCIENTIFIC NAME	COMMON NAME	CHICHESTER	FORTESCUE	HAMERSLEY	ROEBOURNE	EPBC ACT 1999	JAMBA	ROKAMBA	IUCN RED LIST	WCA 1950	NATUREMAP CONSERVATION CODES
Flora	*Acacia cyperophylla* var. *omearana*	O'Meara's minni ritchi	C									P1
	Acacia effusa	Hamersley minni ritchi			H							P3
	Acacia fecunda	Mosquito Creek wattle	C		H							P3
	Acacia levata	Abydos wattle	C									P3
	Acacia subtiliformis	Witarra		F	H						T	P3
	Aluta quadrata	Paraburdoo heath			H							T
	Atriplex eremitis	De Grey saltbush				R						P1
	Eremophila maculata subsp. *filifolia*	Muccan fuchsia	C									P1
	Geijera salicifolia	Hamersley wilga			H							P3
	Goodenia pallida	Mardie fanflower				R						P1
	Hibiscus sp. Canga (P.J.H. Hurter & J. Naaykens 11013)	Channar hibiscus			H							P1
	Lepidium amelum	Oakover peppercress	C		H							P1
	Lepidium catapycnon	Hamersley peppercress	C	F	H		VU				T	T
	Livistona alfredii	Millstream fan-palm	C	F	H							P4
	Myriocephalus scalpellus	Coondiner myriocephalus		F								P1
	Pilbara trudgenii				H							P2

TAXON DATA			IBRA DISTRIBUTION				CONSERVATION STATUS					
CATEGORY FOR WORKSHOP	SCIENTIFIC NAME	COMMON NAME	CHICHESTER	FORTESCUE	HAMERSLEY	ROEBOURNE	EPBC ACT 1999	JAMBA	ROKAMBA	IUCN RED LIST	WCA 1950	NATUREMAP CONSERVATION CODES
Flora	*Pityrodia* sp. Marble Bar (G. Woodman & D. Coultas GWDC Opp 4)	Strelley foxglove	C									P1
	Ptilotus subspinescens	Brockman mulla-mulla			H							P3
	Tetratheca fordiana	Hamersley tetratheca			H							P1
	Teucrium pilbaranum		C	F	H							P1
	Thryptomene wittweri	Mountain thryptomene			H		VU				T	T
	Vittadinia sp. Coondewanna Flats (S. van Leeuwen 4684)	Coondewanna vittadinia			H							P1
Subterranean	*Draculoides mesozeirus*	Middle Robe draculoides	C								T	T
	Ophisternon candidum	Blind cave eel			H		VU			DD	T	T
	Paradraculoides anachoretus	Mesa A paradraculoides			H						T	T
	Paradraculoides bythius	Mesa B paradraculoides			H						T	T
	Paradraculoides gnophicola	Mesa G paradraculoides			H						T	T
	Paradraculoides kryptus	Mesa K paradraculoides			H						T	T
Vertebrate	*Burhinus grallarius*	Bush stone-curlew, Bush thick-knee	C	F	H	R				LC	P4	P4
	Ctenotus augusticeps	Airlie Island ctenotus				R	VU				T	T
	Dasycercus spp.	Mulgara	C	F		R	VU			LC	T	T
	Dasyurus hallucatus	Northern quoll	C	F	H	R	EN			EN	T	T
	Lagorchestes conspicillatus subsp. *leichardti*	Spectacled hare-wallaby	C		H	R					P3	P3
	Leggadina lakedownensis	Lakeland Downs mouse	C	F	H	R				LC	P4	P4
	Leiopotherapon aheneus	Fortescue grunter	C	F	H	R				NT	P4	P4

TAXON DATA			IBRA DISTRIBUTION				CONSERVATION STATUS					
CATEGORY FOR WORKSHOP	SCIENTIFIC NAME	COMMON NAME	CHICHESTER	FORTESCUE	HAMERSLEY	ROEBOURNE	EPBC ACT 1999	JAMBA	ROKAMBA	IUCN RED LIST	WCA 1950	NATUREMAP CONSERVATION CODES
Vertebrate	*Lerista nevinae*	Cape Lambert slider	C								T	T
	Lerista quadrivincula	Four-chained slider				R					P1	P1
	Liasis olivaceus subsp. *barroni*	Pilbara olive python	C	F	H	R	VU				T	T
	Macroderma gigas	Ghost bat	C	F	H	R				VU	P4	P4
	Macrotis lagotis	Greater bilby	C	F	H	R	VU			VU	T	T
	Mormopterus loriae cobourgiana	Little north-western freetail bat	C			R					P1	
	Neochmia ruficauda subsp. *clarescens*	Star finch	C		H	R						
	Notoscincus butleri	Lined soil crevice skink	C		H	R					P4	P4
	Petrogale lateralis subsp. *lateralis*	Black-flanked rock-wallaby		F	H	R	VU				T	T
	Petrogale rothschildi	Rothschild's rock-wallaby	C	F	H	R				LC		
	Pezoporus occidentalis	Night parrot	C	F	H		EN, Mig	EN		EN	T	T
	Pseudomys chapmani	Western pebble-mound mouse	C	F	H	R				LC	P4	P4
	Ramphotyphlops ganei	Gane's blindsnake	C	F	H						P1	P1
	Rattus tunneyi	Pale field-rat				R						
	Rhinonicteris aurantia	Pilbara leaf-nosed bat	C		H	R	VU					
	Sminthopsis longicaudata	Long-tailed dunnart	C	F	H					LC	P4	P4
	Underwoodisaurus seorsus	Pilbara barking gecko			H							P1
Terrestrial invertebrate	*Dupucharopa millestriata*	Dupuch Land snail				R						P2

DETAILS OF MANAGEMENT STRATEGIES

Table A2 Description of actions making up the 17 threat management strategies, including combined strategies, developed by participants during the workshop

MANAGEMENT STRATEGIES	DESCRIPTION OF ACTIONS
1 **Feral ungulate management**	Eradicate where possible, or maintain at low numbers feral donkeys, camels, horses, unmanaged cattle and pigs • Management plan for control measures • Monitoring and evaluation program for eradication effectiveness • Coordinated consistent aerial shooting of all unmanaged introduced herbivores using collar telemetry • Exclusion fencing on all tenures
2 **Domestic herbivore management**	Sustainable grazing practices on pastoral leases (domestic cattle and other livestock) + additional efforts for threatened species • Develop a management plan for the region and each pastoral property • Implement plan: strategic fencing for controlling stock, spell grazing, control access to watering points, managing access to watering points • Exclusion fencing on pastoral tenures • Monitoring and evaluation • Knowledge sharing
3 **Combined feral ungulate and domestic herbivore management**	Strategies 1 and 2 combined
4 **Fire management**	Manage fire using current knowledge with the interim goal of managing fire frequency, intensity and extent for maximum habitat variety (pyrodiversity) for a suite of fire regimes, i.e. create a mosaic of different 'age since burnt' habitats, across all tenures • Develop a central management plan for the region, with over-arching fire management goals • Develop a fire management operational plan for each tenure to be implemented by land managers • Collect key information for planning, monitoring and evaluation • Share knowledge about fire behaviour and management across stakeholders, including traditional ecological knowledge where appropriate • Community awareness through education programs • Implement burning regime: broad-scale aerial burning in summer and winter
5 **Fire management and research**	Strategy 4 + research • Identify the vital attributes (fire ecology) of threatened species, fire behaviour in different regions/land units/systems
6 **Combined domestic herbivore, feral ungulate and fire management**	Strategies 1, 2 and 4 combined
7 **Cat management**	Develop a landscape scale predator control program (e.g. education, get approval for wide scale application of cat baiting, shooting, trapping, and sterilization) • Baiting • Ground shooting localised on conservation estates • Ground shooting on pastoral lands • Leg-hold trapping • Sterilize domestic cats • Education programs for sterilization of cats, keeping cats indoors, cat registration laws

MANAGEMENT STRATEGIES	DESCRIPTION OF ACTIONS
8 **Cat management and research**	Strategy 7 + research • Research into grooming traps • Determine the impact of predators on threatened species in the Pilbara • Identify spatial distribution and densities of predators; develop tools to be able to collect this information • Investigate interactions between dogs, dingoes, cats
9 **Sanctuaries**	Protect vulnerable species in enclosures on mainland and on islands • Establish, manage, monitor mainland sanctuary of adequate size for species persistence, including species reintroduction, translocation • Eradicate black rats on islands • Increased biosecurity on islands
10 **Cane Toads**	Research and monitor cane toads and educate native species • Research on biological control • Surveillance and biosecurity to prevent spread • Research impacts and predictions of likely distribution of cane toads • Sub-lethal doses of toxin to educate threatened native species
11 **Weed management around key assets**	Remove all weeds and follow up removals around key assets (refuge site for threatened species known to occur)
12 **Weed biosecurity team**	Surveillance, detection and eradication of all new weed species
13 **Targeted exotic pasture grasses**	Manage (contain, control, eradicate) exotic pasture grasses (including Buffel grass) and restore after removal, on non-pastoral land
14 **Combined weed and pasture grasses strategy**	Strategies 11, 12 and 13 combined
15 **Hydrology management**	Manage changes to surface and groundwater systems to mitigate threats to threatened species in the Pilbara • Research impact on threatened species to understand impacts • Understand distribution and ecology of cave eel, Fortescue grunter, Millstream fan-palm • Understand and control discharge frequency on ephemeral streams/ replicate the 'natural' system • Develop and implement an integrated water management plan for mines to share water • Understand and control drainage treatment so that natural flows are maintained
16 **Habitat identification, protection and restoration**	Manage habitat modification that impacts threatened species in the Pilbara • Do not remove habitat beyond fixed percentage representation criteria • GIS modelling: vegetation map for predictive modelling, 1:50 scale veg map + ground surveys • Where critical resources must be removed, replicate features of removed areas nearby • Proactive protocol development: develop an understanding of what restoration actually works to inform impact assessment and approvals for projects proposing removal of landscape structures or reconstruction of rocky habitats • Habitat restoration—reconnect fragmented patches to restore landscape connectivity • Determine the impacts of dust, vehicle impacts (off road impacts and collisions), fences, noise and light on threatened species • Collect existing data to identify critical habitat
17 **Total combined strategy**	All strategies 1; 2; 5; 8; 9–13; 15; 16 combined

PARAMETERS

Benefits

The benefits of each strategy were estimated by the improvement in the likelihood of persistence of each threatened species if the strategy was carried out, compared to a baseline scenario that involved no strategies being implemented. The 'likelihood of functional persistence' was defined as the probability that a species would exist over 20 years at high enough levels to perform its ecological function. The likelihood of persistence was estimated assuming that the actions were implemented without delay. Other threats (existing or currently unrealised) were assumed to be constant and continue to impact persistence unless they were altered by the management strategy.

For each of the 17 strategies, workshop participants estimated a baseline likelihood of persistence as well as the likelihood of persistence for each species. For each persistence value participants used the four point approach (Speirs-Bridge *et al.* 2010), which involves estimating a best guess, plus upper (worst-case scenario) and lower (best-case scenario) bounds around the best guess, and a confidence estimate that the real outcome would be between the lower and upper bounds. These estimates were intended to serve as anchoring points to help participants make more informed choices.

Workshop participants made estimates only for those species and strategies for which they felt confident in their knowledge of.

Costs

For each threat mitigation strategy, participants were asked to list the actions that would be involved and the costs of each action.

Table A3 was provided to aid participants with estimation. Wherever possible, costs were based on past experiences undertaking similar actions. Some indicative costs of actions in the Pilbara (e.g. salary cost of a full-time equivalent employee, fencing costs, fire management costs, the per kilometre cost of a vehicle, or the cost of existing feral predator baiting and aerial shooting programs) were provided by DPaW to help participants with cost estimation. Where participants needed extra information to make estimates (e.g. estimation of areal costs where the relevant area was unknown by workshop participants), workshop groups agreed on a method to estimate the cost and the missing data was collected in collaboration with DPaW staff after the workshop.

Participants were given the option of specifying whether costs varied by subregion or tenure.

Table A3 The costs to include and the units used for estimating the costs of actions provided

Include, as applicable, the costs of:

- a Materials, fuel, transport and equipment
- b Labour and/or number of F.T.Es, even if these people are already employed
- c Accommodation, travel etc
- d Lost production (opportunity costs) or compensation for lost production
- e Information gathering or surveys (pre-action)
- f Monitoring for reporting purposes (post-action)
- g Experimental monitoring for adaptive management if learning is part of the action
- h Devising a management plan
- i Capacity building
- j Education and extension
- k Stakeholder engagement processes
- l Co-ordinating implementation

Do not include costs that are incurred as part of management to meet ongoing minimum duty of care requirements

ALL COSTS SHOULD HAVE A UNIT, EXTENT AND TIME PERIOD

UNIT	EXTENT	TIME PERIOD
• $, $K, $M • F.T.E.'s • Hours of labour • Accommodation	• Per ha • Per land management type • Per subregion • For entire treatment area • For entire region	• Once-off establishment costs • Cost over a period (e.g. first five years) • Fixed annual costs • Variable annual costs (give indication of the variable, e.g. rainfall)

Feasibility

Workshop participants estimated the feasibility of the actions in terms of two characteristics: likelihood of uptake and likelihood of success. Likelihood of uptake is the percentage of situations where the strategy would be accepted by the decision maker (e.g. perhaps 50% of pastoralists would be amenable to fire management for biodiversity). Likelihood of success is the percentage of times that the strategy would achieve its stated goals each time it is implemented (e.g. although a fire mosaic may be implemented, perhaps 20% of the time a large wildfire would occur that would overwhelm the mosaic and the benefits of the strategy would not be realised).

To help with estimation, all participants were given the following scale as a guide (*Figure A1*). The feasibility of a strategy was calculated as the product of the likelihood of uptake and the likelihood of success.

Participants were given the option of specifying whether these likelihoods varied by subregion or tenure.

Figure A1 A likelihood scale was provided to the participants as a guide for making prediction on the likelihoods' that a strategy was adopted and would be successful if adopted

CERTAIN	100%
(ALMOST) PROBABLE	85%
LIKELY	75%
FIFTY-FIFTY	50%
UNLIKELY	25%
IMPROBABLE (ALMOST)	15%
IMPOSSIBLE	0%

PHOTO BELOW The Northern Quoll (Dasyurus hallucatus) is found throughout the Chichester and western parts of Hamersley subregion of the Pilbara. The Quoll has a preference for rock habitats such as breakaways and rocky screes although it frequently invades pastoral homesteads and hard rock quarry sites along roads and railways throughout the region.
PHOTO BY Henry Cook, Rapallo.

PHOTO RIGHT *The Pilbara Olive Python (Liasis olivaceus barroni), often frequency rock pools in water courses where it lays in ambush mode with its body submerged except for its eyes and nostril. From this position is can efficiently capture and subdue birds, small mammals like the Northern Quoll and small macropods like Rock Wallabies and Euros.*
PHOTO BY *Darcie Corker, Red Hill Station.*

ANALYSIS

DETERMINING COST-EFFECTIVENESS ACROSS THE REGION AND WITHIN SUBREGIONS

The costs of all actions were converted to a total expected annual cost across the region. In cases where uptake would affect costs, then expected annual costs were determined by modifying the potential cost by the likelihood of uptake. For example if 50% of graziers would be agreeable to a fire management plan, then per property costs were summed for half the number of pastoral properties in the region. The expected present value cost (C_i) of action i over 20 years across the region was then determined using the present value equation which measures the present value of a series of equal payments (C_{annual}) over a number of time steps:

$$C_i = \frac{C_{annual}.t}{(1+r)^t}$$

Where

t varied from 1–20 years depending upon the action and the discount rate was r=7%.
The expected cost of each strategy over 20 years was determined by summing C_i across all actions involved with implementing the strategy.

To determine the cost of actions within each subregion we used a set of rules for allocating costs to the four subregions, which depended upon the nature of the action as follows:

1. Subregion cost = total cost of entire region: research (e.g. cane toad biocontrol) unless specified on a subregional basis
2. Subregion cost = 50% of total cost: management plans, educational programs, information collection
3. Subregion cost is allocated pro rata based on the total area of subregion as a proportion of the region: any per ha costs that are tenure independent
4. Subregion cost = the area of a specific tenure type or number of properties of the region as a proportion of the region: any per ha or per property costs that are tenure specific (e.g. fencing management costs per pastoral property)
5. Subregion cost = total cost/4 (i.e. costs are divided equally between subregions): any costs that are specified per subregion (e.g. three rangers/subregion).

The ecological cost-effectiveness (C_{ei}) of a strategy i in a region is then defined by:

$$CE_i = \frac{B_i\,F_i}{C_i}$$

Where

B_i is the potential benefit of implementing strategy i in the region,

F_i is the feasibility of implementing strategy i in the region (expressed as a decimal between 0–1),

C_i is the expected cost of implementing strategy i in the region.

OPTIMAL SOLUTIONS FOR SECURING SPECIES AT A FIXED PERSISTENCE THRESHOLD

We solve a multi-objective optimization problem to identify the optimal groups of strategies that maximise the number of species above a persistence threshold at a minimum cost. Our optimal solutions are Pareto optimal solutions (Nemhauser and Ullmann 1969). We find the set of optimal strategies that maximizes the number of species above a given persistence threshold (τ) and minimizes the cost of implementing these strategies:

$$\max \sum_{i \in S} \sum_{j \in N} p_{ij} x_i \; and \; \min \sum_i C_i x_i$$

Where

x_i is a binary decision variable that denotes whether or not each strategy is included in the optimal set of strategies. x_i has value 1 if the strategy is selected and has value 0 otherwise. A vector $x \in \{x_1, x_2, \ldots, x_N\}$ represents a combination of selected strategies.

For strategies where the combined effects of multiple strategies were elicited from experts, we constrained the vector x to only allow for feasible combinations of strategies (i.e. combined feral ungulate and domestic herbivore management strategy cannot be associated with domestic herbivore management).

p_{ij} identifies whether species j is expected to reach a given persistence threshold if strategy i is implemented. P_{ij} has value 1 if the expected benefit of applying strategy i for species j is above the persistence threshold

(i.e. $B_{ij}F_i + B_{0j} > \tau$ with $B_{ij} = \sum_{j=1}^{N} \frac{\sum_{k=1}^{M_j}(P_{ijk}-P_{0jk})}{M_j}$).

P_{ij} has value 0 if this threshold is not exceeded.

S is the total number of strategies being considered (S=18).

We solve this multi-objective combinatorial optimization problem by iteratively removing the dominated decisions identifying suboptimal group of strategies.

A decision x' is dominated by a decision x if it secures fewer species and is more expensive to implement.

Table A4, *Table A5* and *Table A6* provide the Pareto optimal solutions for the persistence threshold of 50%, 75% and 90%.

Table A4 Details of the Pareto optimal solutions for a persistence threshold of 50%.

The Pareto optimal solutions provide the best strategies to implement to maximize the number of species secured at a minimum cost.

	WITHOUT STRATEGIES	HYDROLOGY	CAT; HYDROLOGY	SANCTUARIES	SANCTUARIES; HYDROLOGY	COMBINED UNGULATE AND HERBIVORE	DOMESTIC HERBIVORE; SANCTUARIES	COMBINED UNGULATE AND HERBIVORE; SANCTUARIES	DOMESTIC HERBIVORE; FIRE MANAGEMENT AND RESEARCH	DOMESTIC HERBIVORE; FIRE MANAGEMENT AND RESEARCH; SANCTUARIES
BUDGET (MILLION/YEAR)		0.32	0.71	0.80	1.12	1.49	2.08	2.29	3.96	4.76
Mardie fanflower	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Hamersley peppercress	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Coondiner myriocephalus						✓	✓	✓	✓	✓
Coondewanna vittadinia						✓	✓	✓	✓	✓
Teucrium pilbaranum		✓	✓		✓	✓		✓	✓	✓
Hamersley minni ritchi	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mosquito creek wattle	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Abydos wattle	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Witarra	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Paraburdoo heath	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
De Grey saltbush						✓	✓	✓	✓	✓
Muccan fuchsia						✓	✓	✓	✓	✓
Hamersley wilga						✓		✓	✓	✓
Channar hibiscus	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Oakover peppercress	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Pilbara trudgenii	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Strelley foxglove	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Brockman mulla-mulla	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Hamersley tetratheca									✓	✓
Mountain thryptomene	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
O'Meara's minni ritchi									✓	✓
Millstream fan-palm	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Star finch	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Night parrot									✓	✓
Bush stone-curlew	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Fortescue grunter	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Greater bilby			✓	✓	✓	✓	✓	✓	✓	✓

	WITHOUT STRATEGIES	HYDROLOGY	CAT; HYDROLOGY	SANCTUARIES	SANCTUARIES; HYDROLOGY	COMBINED UNGULATE AND HERBIVORE	DOMESTIC HERBIVORE; SANCTUARIES	COMBINED UNGULATE AND HERBIVORE; SANCTUARIES	DOMESTIC HERBIVORE; FIRE MANAGEMENT AND RESEARCH	DOMESTIC HERBIVORE; FIRE MANAGEMENT AND RESEARCH; SANCTUARIES
BUDGET (MILLION/YEAR)		0.32	0.71	0.80	1.12	1.49	2.08	2.29	3.96	4.76
Ghost bat	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Little north-western freetail bat	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Pilbara leaf-nosed bat	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Long-tailed dunnart	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Spectacled hare-wallaby				✓	✓		✓	✓	✓	✓
Black-flanked rock-wallaby				✓	✓		✓	✓		✓
Rothschild's rock-wallaby	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mulgara	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Northern quoll	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Lakeland Downs mouse	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Western pebble-mound mouse	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Pale field-rat				✓	✓		✓	✓		✓
Pilbara barking gecko	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Airlie Island ctenotus	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Cape Lambert slider	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Four-chained slider	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Lined soil crevice skink	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Pilbara olive python	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Gane's blindsnake	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Middle robe draculoides	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mesa A paradraculoides	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mesa B paradraculoides	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mesa G paradraculoides	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mesa K paradraculoides	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Blind cave eel	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Dupuch land snail	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Expected number of species above threshold	**40**	**41**	**42**	**44**	**45**	**47**	**48**	**50**	**51**	**53**

Table A5 Details of the Pareto optimal solutions for a persistence threshold of 75%

	WITHOUT STRATEGIES	FERAL UNGULATE	SANCTUARIES	DOMESTIC HERBIVORE; SANCTUARIES	FIRE MANAGEMENT AND RESEARCH	FIRE MANAGEMENT AND RESEARCH; SANCTUARIES	HABITAT IDENTIFICATION, PROTECTION AND RESTORATION	COMBINED UNGULATE, HERBIVORE AND FIRE MANAGEMENT	SANCTUARIES; HABITAT IDENTIFICATION, PROTECTION AND RESTORATION	DOMESTIC HERBIVORE; SANCTUARIES; HABITAT IDENTIFICATION, PROTECTION AND RESTORATION	COMBINED UNGULATE, HERBIVORE AND FIRE MANAGEMENT; HABITAT IDENTIFICATION, PROTECTION AND RESTORATION	COMBINED UNGULATE, HERBIVORE AND FIRE MANAGEMENT; SANCTUARIES; HABITAT IDENTIFICATION, PROTECTION AND RESTORATION
BUDGET (MILLION/YEAR)		0.39	0.80	2.08	2.68	3.48	4.03	4.17	4.83	6.11	8.20	9.00
Mardie fanflower				✓				✓		✓	✓	✓
Hamersley peppercress	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Coondiner myriocephalus												
Coondewanna vittadinia												
Teucrium pilbaranum												
Hamersley minni ritchi					✓	✓	✓	✓	✓	✓	✓	✓
Mosquito creek wattle					✓	✓	✓	✓	✓	✓	✓	✓
Abydos wattle	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Witarra												
Paraburdoo heath												
De Grey saltbush												
Muccan fuchsia												
Hamersley wilga												
Channar hibiscus												
Oakover peppercress				✓	✓	✓	✓	✓	✓	✓	✓	✓
Pilbara trudgenii	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Strelley foxglove							✓	✓	✓	✓	✓	✓
Brockman mulla-mulla							✓	✓	✓	✓	✓	✓
Hamersley tetratheca												
Mountain thryptomene	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
O'Meara's minni ritchi												
Millstream fan-palm	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Star finch	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Night parrot												
Bush stone-curlew		✓	✓	✓	✓	✓		✓	✓	✓	✓	✓
Fortescue grunter												
Greater bilby												

	WITHOUT STRATEGIES	FERAL UNGULATE	SANCTUARIES	DOMESTIC HERBIVORE; SANCTUARIES	FIRE MANAGEMENT AND RESEARCH	FIRE MANAGEMENT AND RESEARCH; SANCTUARIES	HABITAT IDENTIFICATION, PROTECTION AND RESTORATION	COMBINED UNGULATE, HERBIVORE AND FIRE MANAGEMENT	SANCTUARIES; HABITAT IDENTIFICATION, PROTECTION AND RESTORATION	DOMESTIC HERBIVORE; SANCTUARIES; HABITAT IDENTIFICATION, PROTECTION AND RESTORATION	COMBINED UNGULATE, HERBIVORE AND FIRE MANAGEMENT; HABITAT IDENTIFICATION, PROTECTION AND RESTORATION	COMBINED UNGULATE, HERBIVORE AND FIRE MANAGEMENT; SANCTUARIES; HABITAT IDENTIFICATION, PROTECTION AND RESTORATION
BUDGET (MILLION/YEAR)		0.39	0.80	2.08	2.68	3.48	4.03	4.17	4.83	6.11	8.20	9.00
Ghost bat												
Little north-western freetail bat	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Pilbara leaf-nosed bat												
Long-tailed dunnart					✓	✓		✓			✓	✓
Spectacled hare-wallaby			✓	✓		✓			✓	✓		✓
Black-flanked rock-wallaby												
Rothschild's rock-wallaby								✓			✓	✓
Mulgara			✓	✓	✓	✓		✓	✓	✓	✓	✓
Northern quoll			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Lakeland Downs mouse			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Western pebble-mound mouse	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Pale field-rat												
Pilbara barking gecko			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Airlie Island ctenotus			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Cape Lambert slider							✓		✓	✓	✓	✓
Four-chained slider		✓	✓	✓	✓	✓		✓	✓	✓	✓	✓
Lined soil crevice skink			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Pilbara olive python	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Gane's blindsnake	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Middle robe draculoides	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mesa A paradraculoides							✓		✓	✓	✓	✓
Mesa B paradraculoides	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mesa G paradraculoides							✓		✓	✓	✓	✓
Mesa K paradraculoides							✓		✓	✓	✓	✓
Blind cave eel	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Dupuch land snail	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Expected number of species above threshold	**14**	**16**	**23**	**25**	**26**	**27**	**28**	**30**	**32**	**33**	**34**	**35**

Table A6 Details of the Pareto optimal solutions for a persistence threshold of 90%

	WITHOUT STRATEGIES	CAT	FIRE MANAGEMENT AND RESEARCH	COMBINED UNGULATE, HERBIVORE AND FIRE MANAGEMENT
BUDGET (MILLION/YEAR)		0.38	2.68	4.17
Mardie fanflower				
Hamersley peppercress				✓
Coondiner myriocephalus				
Coondewanna vittadinia				
Teucrium pilbaranum				
Hamersley minni ritchi				
Mosquito Creek wattle				
Abydos wattle				
Witarra				
Paraburdoo heath				
De Grey saltbush				
Muccan fuchsia				
Hamersley wilga				
Channar hibiscus				
Oakover peppercress				
Pilbara trudgenii				
Strelley foxglove				
Brockman mulla-mulla				
Hamersley tetratheca				
Mountain thryptomene			✓	✓
O'Meara's minni ritchi				
Millstream fan-palm				
Star finch				
Night parrot				
Bush stone-curlew				✓
Fortescue grunter				
Greater bilby				
Ghost bat				
Little North-western freetail bat				
Pilbara leaf-nosed bat				
Long-tailed dunnart				
Spectacled hare-wallaby				
Black-flanked rock-wallaby				
Rothschild's rock-wallaby				
Mulgara				
Northern quoll				
Lakeland Downs mouse				
Western pebble-mound mouse				
Pale field-rat				
Pilbara barking gecko				✓
Airlie Island ctenotus				
Cape Lambert slider				
Four-chained slider				
Lined soil crevice skink				
Pilbara olive python	✓	✓	✓	✓
Gane's blindsnake		✓	✓	✓
Middle robe draculoides				
Mesa A paradraculoides				
Mesa B paradraculoides	✓	✓	✓	✓
Mesa G paradraculoides				
Mesa K paradraculoides				
Blind cave eel				
Dupuch land snail				
Expected number of species above threshold	**2**	**3**	**4**	**7**

APPENDIX 2: SENSITIVITY ANALYSIS

To test the effectiveness of the cost-effectiveness rankings to errors in estimates of species benefits, costs or feasibility, we altered the benefits of each of the five highest and lowest-ranked strategies by 20% and 30%.

New rankings were calculated by altering the benefits of strategies one at a time. The rankings of the five highest and lowest strategies are reasonably robust to errors in the estimates of the participants.

Table A7 Sensitivity of highest five ranked actions in the Pilbara

MANAGEMENT ACTION	ORIGINAL RANK	RANK IF BENEFIT DECREASED BY		RANK IF BENEFIT INCREASED BY	
		20%	30%	20%	30%
Feral ungulate management	1	3	3	1	1
Sanctuaries (enclosure or island)	2	3	4	1	1
Cat management	3	3	4	2	1
Domestic herbivore management	4	5	5	4	2
Combined feral ungulate and domestic herbivore management	5	6	6	4	4

Table A8 Sensitivity of lowest five ranked actions in the Pilbara

MANAGEMENT ACTION	ORIGINAL RANK	RANK IF BENEFIT DECREASED BY		RANK IF BENEFIT INCREASED BY	
		20%	30%	20%	30%
Total combined strategy	13	13	15	13	12
Weed management around key assets	14	16	16	14	14
Combined weed and pasture grasses strategy	15	16	16	14	14
Cane toad research and biosecurity	16	16	16	14	14
Weed biosecurity team	17	17	17	17	17

Table A9 Sensitivity of highest five ranked actions in bioregions

MANAGEMENT ACTION	BIOREGION	ORIGINAL RANK	RANK IF BENEFIT DECREASED BY		RANK IF BENEFIT INCREASED BY	
			20%	30%	20%	30%
Feral ungulate management	Fortescue	1	2	2	1	1
Feral ungulate management	Roebourne	2	2	2	1	1
Domestic herbivore management	Fortescue	3	7	9	3	3
Feral ungulate management	Hamersley	4	7	11	3	3
Domestic herbivore management	Roebourne	5	8	12	3	3

Table A10 Sensitivity of lowest five ranked actions in bioregions

MANAGEMENT ACTION	BIOREGION	ORIGINAL RANK	RANK IF BENEFIT DECREASED BY		RANK IF BENEFIT INCREASED BY	
			20%	30%	20%	30%
Cane toad research and biosecurity	Hamersley	60	62	63	58	57
Weed biosecurity team	Roebourne	61	63	64	60	58
Cane toad research and biosecurity	Roebourne	62	63	64	60	60
Cane toad research and biosecurity	Chichester	63	64	64	61	60
Cane toad research and biosecurity	Fortescue	64	64	64	63	63

PHOTO BELOW The Cape Lambert Slider (Lerista nevinae) is Schedule 1 Fauna listed under the WA Wildlife Conservation Act. This small sand swimming skink is restricted to non-continuous coastal dune habitats in the vicinity of Cape Lambert between the old settlement of Cossack on the Harding River and Cleaverville Beach, north of Roebourne. The habitat of the Cape Lambert Slider is threatened by ongoing fragmentation as a consequence of residential and industrial development, basic raw material abstraction and through inundation as a consequence of tidal surges and changes in sea level.
PHOTO BY Glen Gaikhorst, GHD.

***COVER IMAGE** Samphire shrubland (*Tecticornia auriculata *and* Muellerolimon salicorniaceum*)*
on the northern side of the Fortescue Marsh, a wetland of National Significance.
***PHOTO BY** Jeff Pinder, DPaW.*