VEGETATION MAPPING

OF SOUTH WEST FOREST REGIONS

OF

WESTERN AUSTRALIA -

Prepared for:

CALMSCIENCE

**Department of Conservation and Land Management
and Environment Australia**

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MATTISKE CONSULTING PTY LTD

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Vegetation Mapping of the South West Forest Region: Abstract.

Mattiske Consulting Pty Ltd was commissioned by the Department of Conservation and Land Management and Environment Australia to map the vegetation of the South-West Forest Region of Western Australia. The vegetation mapping project enabled the merging of a range of historical data sets, an assessment of the flora values over the southwest forest region and the synthesis of this information into two mapping scales (vegetation complexes at a scale of 1:250,000 and the ecological vegetation systems at a scale of 1:500,000). As a regional mapping project it enabled the merging and integration of a range of data sets on the climate, soils and landform and vegetation patterns. The vegetation complex maps developed by Mattiske and Havel were integrated by Mattiske and Bradshaw to develop the forest ecosystem maps, which were used in the application of the JANIS criteria for the selection of reserves through the Western Australian Regional Forest Agreement process. In addition, the vegetation complex maps developed by Mattiske and Havel (1999) were utilized during the Regional Forest Agreement for boundary verification of the proposed reserves. Consequently, sections of the mapping associated with this CALMScience publication have been available for public use prior to this publiation.

Prior to commencing the vegetation studies, a literature review was undertaken for the project (Mattiske Consulting Pty Ltd, 1997). This review enabled a critical assessment of the proposed methodologies and a documentation of previous studies in the south west forest region.

Evidence is presented to support the concept that the vegetation reflects the underlying geology, landforms, soils and climate. These relationships were observed and recorded by people from the early days of European settlement through the settlers selection of dominant species in determining fertile soils and moister soils. In recent decades, the scientists have confirmed many of these relationships in different areas of the south west forest region; although only in a few instances have the spatial relationships between vegetation and underlying causative factors been mapped.

The floristic and vegetation data sets available for the south west forest region have been collected for the development of floristic or vegetation classification systems rather than for vegetation mapping. The vegetation data was integrated from more than 18,0000 sites and therefore has enabled the merging of many historical databases developed by a range of authors and more recently the team at Mattiske Consulting Pty Ltd.

Previous vegetation maps have been produced at a scale of 1:1,000,000 (Beard 1981); 1:250,000 (Beard 1979a, 1979b and 1979c; Smith 1972, 1973 and 1974; Heddle *et al.* 1980), 1:50,000 (Heddle *et al.* 1980 - base maps for published 1:250,000 maps) and 1:10,000 (Mattiske through E.M. Mattiske and Associates and Mattiske Consulting Pty Ltd for various client projects in the South-West Forest Region). In addition, there were marked differences in the vegetation classification systems, which was at times accentuated by their respective methodologies. Despite differences in data analyses it has been possible to integrate the detailed work of Havel (1968, 1975a, 1975b), Strelein (1988), McCutcheon (1978 and 1980), Inions *et al.* (1989, 1990a, 1990b), Wardell-Johnson (1989) and E.M. Mattiske and Associates and Mattiske Consulting Pty Ltd (1979 - 1996) with the integrated soil and land form mapping by Smolinski (1999), on the range of climatic zones as developed from the work of Gentilli (1989).

Vegetation Mapping of the South West Forest Region.
Part 1: Introduction

Background

Mattiske Consulting Pty Ltd was commissioned by the Department of Conservation and Land Management and Environment Australia to map the vegetation of the south west region of Western Australia as defined under the Regional Forest Agreement between the Commonwealth of Australia and the State of Western Australia.

The vegetation mapping covers 4.25 million hectares of the forest region of the south west region of Western Australia. Essentially it consists of the main forested region in the south west corner of Western Australia, bounded in the south by the Southern Ocean, in the west by the Swan Coastal Plain and the Indian Ocean and in the east by the wheatbelt. Whereas the bulk of this region consists of various categories of crown (publicly owned) land, such as State Forest, National Parks and Nature Reserves, the neighbouring coastal plain and wheatbelt are largely alienated and cleared

The forested region corresponds closely to, but is not fully identical to two Interim Biological Regions defined by the Environment Australia for the National Reserve System, namely Jarrah and Warren (Thackway and Cresswell, 1995). It also corresponds to, but does not exactly match, the system 1 (southwest), 2 (western south coast) and 6 (Darling) defined by the Conservation Through Reserves Committee of the Environmental Protection Authority (1980) in the preceding round of reserve definitions in the 1970's, except that the Swan Coastal Plain is excised. It also corresponds to Beard's (1982) Darling Botanical District, except that the Drummond sub-district, consisting of the Swan Coastal Plain, is excluded. There is also a partial correspondence to Hopper's (1992) high rainfall zone and a close correspondence to the south west forest region of Bradshaw's *et al.*'s (1997).

The current series of maps is envisaged as bridging the gap between Beard's (1981) 1:1 000 000 series, Hopkins and Beard (1999) and Beard's (1979) and Smith's (1972, 1974) 1: 250 000 series of Vegetation Survey of Western Australia, which are primarily based on vegetation structure, and the various localised vegetation classifications and maps of the forested region in which floristics of the vegetation pays a greater role (Havel 1975 a andb, Loneragan 1978, Strelein 1988, Heddle *et al.* 1980, Christensen 1980, Inions 1990 a and b, Wardell-Johnson *et al.* 1989, 1995, Gibson *et al.* 1994, Griffin 1992). The vegetation mapping at the vegetation complex level is an extension of the Heddle *et al.* (1980) maps which covered the System 6 area, in which structure and floristic of the vegetation was combined with environmental factors, in particular geomorphology and climate, to the remainder of the forested region of southwestern Australia

Because the bulk of the vegetation in the two regions consist of either forest or woodland of primarily jarrah (*Eucalyptus marginata* subsp. *marginata* and *Eucalyptus marginata* subsp. *thalassica*), mapping on structure or dominance has severe limitation. The bulk of variation in the vegetation resides in the shrub and herb storey, which is composed of between 1800 and 3000 species. Past quantitative studies have demonstrated the feasibility of subdividing the structurally uniform vegetation of the region on the basis of floristics. However, direct mapping of floristically homogeneous communities (or site-vegetation types) at the scale of 1:10,000 to 1:25,000 requires intensive fieldwork and is costly and slow.

In this project the geomorphologic maps covering the two bioregions were converted into maps of vegetation complexes by using climatic data and outputs of localised quantitative vegetation studies.

The annual median rainfall discounted by summer (December to February) evaporation was used as the key broad scale determinant of vegetation patterns. Within the climatic zones thus generated the moisture balance was considered to be further modified by landforms, ranging from steep slopes with shallow soils, which have no capacity to store winter rainfall toward summer transpiration, to depressions with prolonged water accretion or to deep soils capable of storing the bulk of the incoming rainfall. Landforms were also considered to be the determinants of fertility, the extremes of the range being loamy soils freshly developed over basic crystalline rock and highly leached sands that have been through more than one cycle of soil formation. The resulting maps at the scale of 1:250,000 were then combined into a single map of vegetation systems at the scale of 1:500,000.

The systems were defined as segments of the vegetation continuum associated with a particular combination of climate and landform. The degree of dissection and hence the fertility of the site is reflected in the intensity of the colour. Steep slopes with fresh fertile soil are indicated by darker shades of colour. Mild slopes with reworked siliceous soils are indicated by pale shades. Intermediate slopes with gravelly lateritic soils are indicated by medium shades. The colour scheme used primarily reflects the water balance of the site and the composition and structure of the vegetation it supports. The woodlands of xeric sites of the arid – perarid zone are coloured yellows and orange. The tall open forest of hyperhumid sites is coloured mauve or blue. Intermediate sites are coloured yellow-green and green. Extreme sites are coloured red (eg. the main granite outcrops).

Review of Past Ecological Classification and Mapping

Early Floristic Mapping

Gentilli (1979a and 1979b) summarised and reviewed the early floristic maps. The first floristic map was produced by C.Woodhouse in the Surveyor-General's Office in 1880. This map (at a scale of 1:1,170,000) covered the forest areas within the State and was the first attempt to define forests in the area from Moore River to Pallinup River. This map distinguished the six dominant tree species - jarrah *(Eucalyptus marginata)*, karri (*Eucalyptus diversicolor*), 'white gum' or wandoo (*Eucalyptus wandoo*), 'tooart' or tuart (*Eucalyptus gomphocephala*), York Gum (*Eucalyptus loxophleba*) and 'red gum' or marri (*Corymbia* (formerly *Eucalyptus*) *calophylla*). This early work illustrated the distribution of the dominant tree species in the south west forest region of Western Australia.

This early work was followed by a series of successive floristic maps, which illustrated the broader floristic regions within the State (Drude 1884, Sievers 1895). This earlier tradition of floristic maps of dominant forest species was continued by Moore (Ednie-Brown 1896, 1899), Lane-Poole (1920) and latter by Hall *et al.* (1970), Chippendale (1973) and Brooker and Kleinig (1990). In recent years substantial taxonomic studies have led to revisions of many of the species which dominate the South West Forest Region including the subdivision of jarrah (*Eucalyptus marginata*) into three subspecies (Brooker and Hopper 1993) and wandoo (*Eucalyptus wandoo*) into 4 species and 6 species and or subspecies (Brooker and Hopper 1991).

Early Vegetation Mapping

An early attempt at vegetation mapping was undertaken by Schimper (1898) who highlighted the first attempt to show sclerophyllous woods in the south west region of the State. Shortly after Diels (1906a and 1906b) produced the first structural map of Australian vegetation.

Diels 1906a and 1906b

Although the botanical collections and descriptions in southwestern Australia date back to colonization in the 1830 (Drummond), the first major attempt to classify and map the vegetation was that of Diels (1906a and 1906b) in his classic Die Pflanzenwelt von West Australien sudlich des Wendeskreises - The Plant World of Western Australia South of the Tropic.

The work of Diels was ambitious as it was undertaken at a time when transport was limiting, and perceptive as it defined relationships between the vegetation and the underlying environmental factors, especially climate and soils. The key perception was that the vegetation of the south west has no counterpart in Mediterranean regions elsewhere in the world, in particular the presence of tall trees with vertical leaves, the strong development of hard-leaved shrubby understorey and the replacement of the grasses and annuals by perennial herbs of the families Cyperaceae and Restionaceae. He also identified the great floristic richness of the vegetation in spite of, or perhaps because of, the extreme infertility of the sandy and gravelly soils.

Apart from the forest formations, Diels also described swamp and granitic rock formations, giving a brief enumeration of species for each.

As a plant geographer, Diels was interested in endemism, which has considerable bearing on the detection of plant indicators. He considered the jarrah forest to be relatively poor in endemics amongst its 875 species, with the endemism at a maximum near its northern limit, where the climatic gradient is steepest. For the South-West province as a whole, he listed *Lyginia, Anarthria, Dasypogon, Kingia, Phlebocarya, Conostylis, Synaphea* and *Nuytsia* as first-class endemics, that is without any relations outside, and *Desmocladus, Diplolaena, Platytheca, Tremandra, Hypocalymma, Calothamnus* and *Andersonia* as second-class endemics, that is with some relations outside but markedly different from them.

Finally, Diels subdivided the south west province into seven botanical districts. The survey area falls chiefly into the eastern upland portion of the Darling District, described as gravelly, hilly country within the 600 to 1000 mm rainfall zone, also containing some swampy alluvium and sands. Jarrah is used as the character species. The north east portion of the area falls into Diels' Avon District, and the south east portion into the Stirling District.

Other Early Vegetation Mapping

Several authors contributed to the vegetation mapping in the period from 1906 to 1940, although these studies were relatively minor for interpretations in the south west region. Hardy (1911) defined the forest areas as "winter rain forest" which recognised the potential role of climate conditions in determining forest boundaries.

Gardner's (1923) description was little more than a brief summary of Diels' work in English. It was followed by a vegetation map in 1928.

Geisler (1930) included the dominant floristic element in each plant formation and his accuracy on the dominant species appears to reflect a certain degree of regional knowledge of the State. The overall description of the vegetation of Western Australia by Gardner (1944) elaborated on the work of Diels, and added to the knowledge of areas not visited by him, but the scheme of classification was essentially that of Diels. The jarrah forest was mentioned only briefly, with no additional information.

Prescott's (1931) vegetation map is well known, although it did not differ substantially from the earlier map of Gardner (1928). Wood (1950) published a map, which included a more realistic appraisal of the characteristics of the Australian vegetation. These three latter authors all recognised the significance of climate in determining forest types, although some differences were noted in their interpretations on "wet sclerophyll forest", "dry sclerophyll forest" and "temperate Eucalyptus rain forest" and "mesophytic forest".

Forests Department - Aerial Photographic Interpretations

Following the Second World War, the Forests Department utilised the technology developed for aerial reconnaissance to map the areas under its control from black and white photography. The outcome of this photo-interpretation work was mapped at a scale of 1:63,360 and by 1970 covered the entire forest region to the stage where it could be used by Smith (1972, 1973, 1974), Beard (1979a, 1979b and 1979c) and Heddle *et al.* (1980a), in association with their own vegetation mapping work. The Aerial Photographic Interpretation (API) maps chiefly described and mapped the structural features of the vegetation, such as height, class and crown cover. Only some of the species with characteristic structural features can be identified on the aerial photographs, for example karri (*Eucalyptus diversicolor*), rock sheoak (*Allocasuarina huegeliana*) and the swamp paperbark (*Melaleuca preissiana*).

Williams 1932 and 1945

The chief source of early detailed ecological information is Williams (1932, 1945), who carried out two small-scale site-vegetation studies in the north western corner of the survey area. One of these was situated on Cohen Brook, a minor tributary of the Helena River, at the point where it descended from the Plateau on to the coastal plain. The other was situated in the valley of the Darkin River, the main tributary of the Helena River, approximately 27 kilometres inland from the edge of the Plateau. The areas covered were 17.8 ha and 74.5 ha respectively. In both cases, the landscape was, by local standards, strongly dissected, the laterite capping occupying a very much smaller proportion of the total landscape than was true of the northern jarrah as a whole. Consequently there was much outcropping of the underlying rocks, namely granite with epidiorite dykes. In the Darkin study, a narrow zone of alluvium was also encountered. The observations were done with painstaking detail, the position of each tree being mapped and total enumeration of all perennials being carried out on one per cent of the area on a 20m x 20m grid. The second survey was somewhat less detailed. On the basis of these surveys, Williams described several associations and consociations, the latter being communities dominated by a single tree species: *Corymbia calophylla*, *Eucalyptus wandoo*, *Eucalyptus marginata* and *Eucalyptus patens*.

Holland 1953

In Holland's (1953) study of eucalypt distribution patterns, no new work was reported, apart from one transect and one small pot trial. The latter transect spanned the topographical gradient from lateritic upland to wet alluvium, that is, from jarrah through wandoo and marri to flooded gum (*Eucalyptus rudis*). Relatively few associated species were named. Marri was considered to be more flexible in its habitat requirements than jarrah, which was considered to be incapable of competing on good soils and to have a narrow tolerance to moisture fluctuations. A novel idea was the recognition of eroded valleys as migration routes. The present distribution of species was considered to be the result of past expansions and contractions. Presumably this was based on studies in the southern Eremean region as no detailed evidence was presented for the jarrah region.

Williams 1955 and Sochava and Korchagin 1970

William's map in 1955, followed on from the earlier studies of Wood (1950) and was based on strictly structural characteristics. Sochava and Korchagin (1970) in adapting William's 1955 map defined twenty-three types of vegetation, which raised the degree of classification for the State. Since William's work a series of maps have been produced for Australia including Cochrane (1967), Moore (1970) and later Carnahan (1976).

Speck 1958

The next study of south western vegetation was that of Speck (1958), who worked within the framework established by Diels, but introduced several new methods and ideas. Although his work was not strictly quantitative, greater details were incorporated, particularly on Diels' Irwin Botanical District. From his data he attempted a classification of plant communities using the nomenclature of Beadle and Costin (1952), slightly modified for local conditions but retaining the emphasis on structure as the first criterion of classification. Three major formations were described; forest, woodland and scrub. The latter was defined as depauperate trees or shrubs in a continuous stratum, with subordinate shrub layer but poorly developed herb stratum. The three formations were further subdivided into 24 sub-formations and 62 plant communities, largely, though not exclusively, described as association. The association was defined as a climax community in which the dominant stratum exhibited a quantitatively uniform composition throughout its range. The dominants were used as the characteristic species. The associations were grouped by their structure into structural formations, and by similarities in both floristic composition and structure into alliances. The use of profile diagrams to illustrate the structure of plant communities was one major advance on the work of Diels.

Within the northern forest region, Speck recognized three vegetation systems. Of these, the Darling System, which covers the Darling Scarp and the western margin of the Plateau, contains some youthful streams and has an annual rainfall of over 890 mm. The Bannister System, which was restricted to the eastern margin of the area, away from the Scarp, lacks youthful streams and has an annual rainfall of between 500 and 1000 mm. Each has a set of plant communities ranging from the *Eucalyptus marginata* to *Corymbia calophylla* high forest to *Eucalyptus wandoo* woodlands. However, whereas the Darling System was described as the 'prime' jarrah forest, the Bannister System was merely looked upon as its poorer eastern extension. The associations observed were:

(I) *Eucalyptus marginata*;
(II) *Eucalyptus marginata – Corymbia calophylla;* and
(III) *Eucalyptus wandoo* in both systems;
(IV) *Eucalyptus patens;* and
(V) *Eucalyptus megacarpa* in Darling only;
(VI) *Eucalyptus wandoo-Eucalyptus accedens* and
(VII) *Eucalyptus accedens* in Bannister only.

Profile diagrams, structural formulae and brief species lists were used to illustrate the high forest of *Eucalyptus marginata-Corymbia calophylla* and the tall, temperate woodland of *Eucalyptus wandoo-Corymbia calophylla*. Only brief mention, without any species list, was made of *Eucalyptus patens* and *Eucalyptus megacarpa* associations. North of the Darling and Bannister Systems, that is north of the Avon River, Speck described the Chittering System, characterised by strong dissection of the plateau and the predominance of woodland rather than forest.

The relevance of Speck's work is that it provides a broad framework within which the more detailed survey of the northern jarrah forest can be fitted.

Lange 1960

Lange (1960) related climatic and edaphic factors to distribution of tree species in the Narrogin district. Although much of his study area was east of the Jarrah bioregion, many of the tree species studied by him occur within the survey area, and their distribution in a drier climate throws considerable light on their site requirements. Lange found that the 500 mm isohyet was the main dividing line between the western species characteristic of acid, lateritic soils and high rainfall, such as *Corymbia calophylla, Eucalyptus marginata, Eucalyptus rudis, Banksia grandis* and *Nuytsia floribunda*, and the eastern species characteristic of the calcareous, alkaline soils of the dry inland, such as *Eucalyptus salmonophloia* and *Eucalyptus longicornis*. However, a number of tree species, namely *Eucalyptus wandoo, Eucalyptus loxophleba, Eucalyptus astringens, Acacia acuminata* and *Allocasuarina huegeliana* straddle the 500 mm isohyet. Whenever the western species occur east of the dividing line, it is invariably as outliers on deep lateritic soils or on sandy soils in moisture-gaining depressions. He attributed the disjunct occurrence of the western species to an arid period in the late Quaternary, as postulated by Crocker (1959). The overall effect of increased aridity was the contraction of these species to favourable sites.

Churchill 1961 and 1968

Past climatic fluctuations were the subject of palynological investigations by Churchill (1961-1968), who was concerned primarily with the vegetation of the extreme south-west, in particular the balance between *Eucalyptus marginata, Corymbia calophylla* and *Eucalyptus diversicolor*. Major changes in pollen spectra were dated to 3000 B.C., 1200 B.C., A.D. 400 and A.D. 1200. He concluded that a drier climate, favouring the increase of *Corymbia calophylla* at the expense of *Eucalyptus diversicolor* (now largely restricted to high-rainfall areas along the south-western and southern coast) probably occurred between 3000 and 5000 B.C., and between A.D. 500 and 1200. Moister climatic conditions favouring *Eucalyptus diversicolor* probably occurred prior to 3000 B.C., between 500 B.C. and A.D. 500 and from A.D. 1500 onwards. The incorporation of charcoal in the peat deposits indicated that fire has been part of the environmental complex for at least 7000 years.

Specht 1970

Specht (1970) developed a new system of vegetation mapping for Australia based on projective foliage cover and height of the tallest stratum. Although this study was not confined to the south west forest region of Western Australia it enabled a degree of consistency to be developed in the work undertaken in the region and also enabled some uniformity with other classification systems throughout Australia. This system relied on the main structural characters and dominant floristics (e.g. open forest of jarrah-marri).

Smith 1972, 1973 and 1974

Smith (1972, 1973 and 1974) carried out a series of vegetation mapping projects in the Collie, Pemberton to Irwin Inlet and Busselton and Augusta areas of the south west, Western Australia for the Department of Agriculture under the auspices of the Western Australian Vegetation Survey Committee. The initial mapping was carried out at the scale of 1:250,000, using aerial photo interpretation. The criteria used in the description and classification of vegetation were the lifeform and height of the tallest tree stratum and the projective foliage cover of the tallest stratum expressed as percentage. These criteria were incorporated into the descriptive title of the structural vegetation type, such as high open forest, low woodland or heath.

Sources of information for this mapping were the 1967 aerial photographs at a scale of 1:40,000 and the Forests Department's Aerial Photographic Interpretation (API's) plans which provided some additional information on vegetation structure and principal trees occurring in forested areas. In addition traverses by motor vehicle and on foot were made during the period June 1971 to August 1972 covering the routes illustrated on the border of the vegetation map. Subdivisions of the structural formations on the basis of plant associations is indicated by means of symbols. This mapping was most effective around the coastline, where the vegetation varies from herbland to forest. It was moderately effective in the karri region, where it distinguished well between the tall open forest of karri, marri and tingle and the open forest of jarrah. It was also fairly effective at the eastern margin of the forest, where it distinguished between the open forest of jarrah and the woodland of wandoo. It was relatively ineffective in the main central belt of forest, the bulk of which fell into the category of open forest dominated by jarrah.

Havel 1968, 1975a and 1975b

The next attempt at the classification of the forests and woodlands of the region was that of Havel on the northern Swan Coastal Plain between 1965 and 1968. Whilst geographically the study was outside the main region under consideration, it is significant that the concepts and methodologies that dominated the forest classification for the next two decades were developed and tested there under a relatively simple and narrow set of edaphic, topographic and climatic conditions. Had it been applied to the main forest region initially, it may have been given up as too difficult. In addition, many of the ecological groupings defined there, and the relationships established between soil fertility and soil moisture regimes, are highly relevant to three of the subregions within this project. These three subregions are the Blackwood Plateau, the Scott Plain and the South Coastal Plain, with which it shares the prevalence of infertile, siliceous soils and mild topography.

The first point of departure from previous studies was that it was undertaken as applied ecological project, in which understanding of the vegetational patterns was not the end in itself, but only a means to an ecologically based land management system. Initially the latter study, was undertaken as a basis for land classification for plantation forestry. Its initial aim was to use of vegetation to predict site productivity, because the depths of the sand dune systems made soil surveys difficult and of limited use.

The second major point of departure was that new methodology was adopted. This was not deliberate. To begin with, methodology of European forest ecology was examined in detail. However, it was found that the well defined plant associations of Braun Blanquet (1932) and the clearly defined biogeocenosis concepts of Sukachev (1954), that worked for the European vegetation strongly modified and fragmented by millennia of human impact, were of limited use in south western Australia, where the relatively undisturbed and species rich forest and woodland understorey lacked clearly defined boundaries and tended to form continua in which the changes were progressive. Attention was therefore turned to other European approaches to vegetation classification, such as the vegetation-based site classification system of Cajander (1926) and Ilvessalo (1929) in Finland. The concept of a continuum of forest types, based on the composition of the understorey, was more applicable to the situation in the south west. However problems were encountered when the method was tried under local conditions. Its success in Finland was made feasible by the relatively depauperate and simple vegetation of that country. However, the simple, subjective methodology was inadequate to deal with complex and species rich vegetation of the south west forest region of Western Australia.

Attention turned to more objective methodologies for dealing with continua. Of these that of Pogrebnjak (1955), namely the ordination (edaphic net) developed for the forest-steppe transition in Ukraine. A similar method to that of Pobrebnjak's approach was subsequently used successfully in the United States of America by Whittaker (1956). It proved good for illustrating a broad picture of the relationships between vegetation and the environment The problem with all these methods was that the vegetation was arranged on the basis of environmental parameters. However, what was needed in south western Australia was the understanding of vegetation patterns that could be used to infer environmental conditions. There was a methodology that already attempted that, namely the ordination through environmental indices, developed in the United States of America by Bray and Curtis (1957). The essence of this approach was that as the vegetation reflects environmental conditions, the vegetation patterns should reflect the environment. This methodology of Bray and Curtis was also tried, but at that stage it proved fairly subjective and labourious.

Attention therefore turned to computer based classifications being developed in Australia by Goodall (1954, 1963), who at the time was working for CSIRO in Western Australia. This methodology was factor analysis, or more precisely principal component analysis. It was objective and capable of handling large volumes of data. With Goodall's's guidance and help a system was developed that has been used over the next twenty years over much of the south-western forests.

The pattern of the sampling was a cluster of plots in native vegetation which surrounded the experimental pine plots. There were four tree plots of 40m x 10m, within each of which were nested two shrub sub-plots of 4m x 4m (metric equivalent of 13ft x 13ft). The parameters recorded were the basal area of the trees and the presence of the understorey shrubs and perennial herbs, converted into frequency over the eight subplots. Within each plot, soil samples were taken at two levels, equivalent to 0-1 and 1-2m, which were analysed in the laboratory for soil reaction and the percentages of iron and organic matter, suspected to be the chief determinants of moisture and nutrient holding capacity of the sands.

Because of the limitation of the programme the shrub data had to be reduced to thirty species of moderate to high frequency. Rare and common species were omitted.

The output of the principal component analysis identified the degree of the leaching of the soil, expressed as percentage of iron, as the key determinant of vegetation patterns. The second key determinant was moisture availability.

As the exotic trial plots used in the original analysis did not adequately cover the full range of environmental factors, the extreme sites, in proximity to swamps and limestone outcrops, were studied by Pogrebnyak's (1955) method of edaphic net. To obtain data for these, extreme sites transects were established in locations where a clear catena of edaphic conditions existed, such as from swamp to dune crest, and from dune swale to limestone outcrop. The dimensions of the segments of these transects were comparable to that of the earlier phase of the study, namely tree plot 40m x 40m, containing eight 4m x 4m shrub and herb quadrats each. As in the case of the earlier sampling, soil samples were taken, but instead of being only once-off samples of chemical parameters, they were continued as bi-monthly samples of soil moisture contents for a full year. Subsequently they were resumed on yearly basis as part of a environmental study of the effect of natural rainfall fluctuations and groundwater extraction on groundwater levels (Heddle 1980) and have continued up to the present time. Combined with annual and more recently triennial assessments of the vegetation data they provide one of the longest studies of vegetation dynamics in Australia from (1965 to 2000) (Havel 1968; Heddle 1980; E M Mattiske and Associates 1995, Mattiske Consulting Pty Ltd 2000). The study had influence beyond its original narrow objective of site classification for plantations.

The edaphic nets developed on the basis of the transect surveys confirmed and expanded the findings of the principal component analysis, and on their combined basis eleven site vegetation types were defined, each with a set of indicator species. The types were considered to be noda in a multidimensional continuum, not narrowly defined plant associations of the European classification systems.

Many of the indicator species have re-emerged subsequently as indicators in vegetation studies of other regions, where they are largely, though not exclusively, associated with siliceous sands. Significantly, they emerged as indicators even in regions with nearly twice the rainfall of the northern Swan Coastal Plain.

Before the results of the studies were published, the workability of the system was tested by extensive field surveys covering 3307ha in five localities. The differences due to fertility, which are reflected in the composition of the shrub stratum, were more difficult to map, requiring ground surveys. Those due to water availability, which is reflected in the composition and structure of the tree overstorey, were detectable on aerial photos. It was found possible to map the site-vegetation types effectively. by a combination of ground surveys and aerial photo-interpretation.

Subsequently, the classification was applied to the bulk of the State Forest on the Swan Coastal Plain north of Perth. One of the significant by-products of this was that several areas of high ecological diversity were recognised, and set aside and became part of the reserve system, with economic activity being directed to areas of low diversity, better suited for broadscale mechanised operations.

With the site-vegetation classification of the northern Swan Coastal Plain completed and site mapping becoming a routine procedure in late sixties, Havel turned his attention to the northern jarrah forest (Havel 1975a and 1975b). The initial objective was similar to that for the northern Swan Coastal Plain, though it was widened to include the productivity assessment of indigenous hardwood forests as well as the potential for plantation establishment. However, as the work proceeded the social and economic environment entered a period of rapid change (Havel 1989). Economic developments such the expansion of the bauxite mining and of water harvesting made timber harvesting, which was already declining, less significant than it had been for the past century. The growth of public concern over these activities, over the salinisation of the streams and over the spread of the dieback disease changed the perception of the forest from an economic resource to that of protector of water supplies, a recreational resource and an entity with a value of its own, requiring protection and conservation. By the end of the study the objective of the vegetation surveys changed to the provision of sound ecological base for conservation and multiple purpose management.

As the area to be classified and mapped was greatly more extensive (732,600 ha compared to 51,030 ha) and diverse (in terms of geology and climate), changes in methodology also became necessary. Fortunately, the developments in computer technology and quantitative ecology were equally rapid. The sampling comprised 320 plots of 40m x 40m, each containing 16 quadrats (subplots) of 1m x 1m. Total enumeration of all trees in terms of basal area was carried on the large plots and total enumeration of perennial shrubs and herbs in terms of percentage cover on all the subplots. The enumeration of the vegetation was accompanied by soil sampling and the description of the topographic and edaphic features of the plot. The analysis of the soil data included both physical and chemical (pH, N, P, K, Ca, Mg, CEC and Saturation) features.

In spite of the rapid development of computer technology the data pool (364 perennial species on 5120 quadrats) required reduction before computation could be carried out to a satisfactory conclusion. The cover values for the 16 quadrats within each tree plot were summed up, and the frequency of occurrence of the individual species within the data base was used to eliminate those too rare to be of practical use in mapping or too common to have discriminatory power. Species which could not be reliably identified on foliage alone were also excluded, as much of the data collection had to take place in the dry season, after flowering ceased. In any case, the capacity of the program then available for the principal component analysis was limited to 80 species. Difficulties were experienced even after the reduction to 80 species, in that the program could not proceed beyond the calculation of the correlation matrix. The groupings of the species on the correlation matrix indicated correspondence with the more obvious plant groupings in the field. The correlation matrix was therefore used to further reduce the number of species by eliminating those that failed to show adequate correlations with other species and would therefore be unlikely to be of value as indicators.

With the reduced data pool it was possible to progress the principal component analysis up to the stage of normal loadings for the species, and to advance it by auxiliary programs (FACVA) to obtain scores for the plots, so that it would be possible define ecologically equivalent or at least similar sites.

The program was also used to test the discriminatory capacity of any species, by observing how tightly or loosely the occurrences of a species were clustered within the principal component space, to which component it was responding or for which group or groups of plots, or for which environmental attribute, it could serve as an indicator. Altogether 128 species were tested, and of these 55 were chosen for the second run of the principal component analysis.

The ultimate output of the process was the definition of 19 plot groups, defined by 23 groups of indicator species. The range of environmental attributes such as topography and soils was also described for each plot group, defined as site-vegetation type. The types were considered to be noda in a four-dimensional continuum, not tight plant association. They were indexed by letters of alphabet for convenience in field mapping, as the definition by the names of several indicator species would be too cumbersome.

Alternative methods of classifications were also used, namely the monothetic divisive classification, using programs DIVINF and DIVINFRE, and the agglomerative polythetic classification using program CLASS. Of the two classifications, CLASS appeared to be more robust and better able to deal with a continuum. The groupings of plots (normal analysis) that it generated were homogeneous and similar to that arrived at by the ordination process described earlier. The process by which they were arrived could not be readily traced, because each division was based on several species. The grouping of species (inverse analysis) was less satisfactory, giving some very small and some very large groups. The process also gave no indication about the value of individual indicator species, other than by showing their association with the groups of plots defined by the normal analysis.

The monothetic divisive classification (DIVINF and DIVINFRE) had the advantage that the successive divisions, based on single species (normal analysis) or single plot (inverse analysis), could be more easily traced, but the process was less robust, because it was based on single individual, and the groups generated were less homogeneous. The groups derived by a long succession of negative decisions were particularly vulnerable, as they had little in common other than the absence of the species or plots used in the division process, and were thus quite heterogeneous.

McArthur and Clifton 1975

In the southern half of the study area, a broadscale account of climate, landforms and vegetation was developed by McArthur and Clifton (1975) for the Pemberton district as an aid to land use planning. Some of the concepts developed by them were a starting point for subsequent more detailed studies, in much the same way that the work of Speck (1958) did in the north.

Basically, they first reviewed past soils studies in light of the new nomenclature of Northcote (1974), defined the dominant soil types within the region and then mapped several subdistricts arranged in a continuum from the Darling Plateau in the north, through the dissection of the plateau toward the southwest, the zone of isolated granitic hills and broad sandplains further south and finally the southern coast, with its succession of sand dunes. In each survey area they described an association of soils and having discussed the component soil types, they looked at the relationship between these soil types and the vegetation that they carried in the light of climatic conditions.

They described the vegetation in terms of Specht's (1970) formations, but also gave tables of component species for these formations. Whilst their description of vegetation is largely just descriptive and not based on any formal analysis of quantitative samples, it was a very useful first step in the right direction for the southern region.

This study recognised that the distribution of the species and vegetation formations was controlled by combination of rainfall, soil, landform and aspect. There was a recognition that the climatic gradients across the area were influencing the vegetation; although the single most significant factor in determining the vegetation was the soil. The authors defined the main vegetational features and characteristics in relation to the soil associations (Balbarrup, Perup, Nyamup, Pemberton, Boorara, Chudalup, Blackwater, Quagering, Meerup, Yeagerup, Carey, Coolyarbup and d'Entrecasteaux). As reflected in other earlier studies, there was a recognition that there were subsets of vegetation units within these soil associations which largely reflect subtle soil and soil moisture changes.

Loneragan 1978

Concurrently and parallel with the work of Havel, but independent of him, Loneragan (1978) studied the interface between forests and woodlands of jarrah (*Eucalyptus marginata*) and wandoo (*Eucalyptus wandoo*). The two studies had much in common: both took the earlier work of Speck (1958) as a starting point, both derived their methodology from and received advice and assistance from Goodall (1954). There was even an overlap in the study area, in that Loneragan derived his samples from the northeastern quadrant of the area covered by Havel, and extended it further to the north and east. The chief differences were in the objectives of the studies and resources available to the two researchers.

Whereas Havel's objective was applied and considerable resources, especially in terms of manpower, were available to him, Loneragan work was done toward a PhD thesis and was limited in resources. By the very choice of methodology both implicitly accepted the possibility that the vegetation of south western Australia forms a continuum. Whereas Havel's objective was the subdivision of that continuum into manageable segments useful in forest management, Loneragan asked the more basic question such as whether the continuum really existed and whether it could be subdivided in a statistically valid way.

Whereas Havel's samples were tied to locations of significance of forest management and were to that degree predetermined, Loneragan's samples were located on stratified random basis, though he was forced to make concessions to logistics by accepting only samples within 0.8 km of a road. An important specification made by Loneragan was that no sample could be closer than 50m from any well-defined stream-bed, which automatically eliminated the moist end of the vegetation continuum.

Ultimately Loneragan selected 122 sample plots. The data collected by Loneragan was comparable to that of Havel (1975a), in that trees were recorded on 48m x 48m plots in terms of numbers and basal area, and shrubs and herbs were recorded on 16 1m x 1m quadrats. The shrub species were recorded in terms of frequency out of the sixteen quadrats, and in terms of canopy cover on the four central quadrats. The environment was described in terms of geomorphology, topography and soil, the latter both in terms of field profile and laboratory sampling of physical and chemical properties. Rainfall for the plot was estimated statistically.

The statistical analysis of the data was more extensive than that of Havel (1975a). The tree data was first tested for the homogeneity of distribution. The enumeration of the tree species indicates that extreme sites, that is those very wet, very sandy or very drought prone were not sampled, namely - no *Melaleuca preissiana, Banksia littoralis, Banksia attenuata* or *Allocasuarina huegeliana*, which are typical of these sites, were included in the test.

Loneragan also subjected the tree data to clustering using Goodall's Probabilistic Similarity Index (PSI) and derived six major groups. In some of these there was a clear dominance of one tree species, such as wandoo (*Eucalyptus wandoo*) (T1), powderbark wandoo (*Eucalyptus accedens*) (T2) and jarrah (*Eucalyptus marginata*) (T4, 5 and 6). marri (*Corymbia calophylla*) was not a clear dominant in any group but an associate of all other species. In the T3 cluster all four species were present in significant proportions. In T4 jarrah was accompanied by all other species, both the eucalypt co-dominants and non-eucalypts sub-ordinates (*Banksia grandis, Allocasuarina fraseriana, Persoonia elliptica* and *Persoonia longifolia*). Wandoo and powderbark wandoo were absent from T4 and T5. In T5 the only subordinates were *Banksia grandis* and *Persoonia longifolia*, in T6 all four non-eucalypt were present. By comparing the PSI clustering with Speck's (1958) structural classification the three groups dominated by wandoo (T1-3) fell largely into Speck's woodland formation, those dominated by jarrah (T4-6) into forest formation. The matching was less clear at the level of floristic associations, in that several associations fell into one PSI cluster, and several PSI clusters into one association. The location of the PSI clusters within the survey region was quite informative, the wandoo and powderbark wandoo dominated clusters falling largely into the northern and eastern sectors, though there were westward extensions of the wandoo clusters, in particular T1, along the river valley systems. Of the jarrah-dominated clusters the T4 cluster extended from east to west, whereas the T5 and T6 clusters were largely confined to the southwest. Loneragan concluded in the light of the above findings that the two major groupings, namely the wandoo alliance (T1-3) and the jarrah-marri alliance (T4-6) comprised two vegetation systems related to two different environments.

Ordination of the tree data by means of PCA omitted species of low frequency, namely *Eucalyptus patens, Acacia acuminata* and *Acacia saligna (Acacia cyanophylla)*, all of which tend to occur in valleys, thus further pushing the data set toward the uplands. The remaining species were first evaluated in terms of Importance Value (IV), percentage Constancy (%C) and number of occurrences (n), and ordered in terms of their dominance within the stands. Jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla)* occurred in 91 stands, wandoo (*Eucalyptus wandoo*) in 55 stands and powderbark wandoo *(Eucalyptus accedens*) in 18 stands, mainly as dominants or co-dominants. All residual non-eucalypt trees (*Persoonia longifolia, Persoonia elliptica, Banksia grandis* and *Allocasuarina fraseriana*) occurred as subordinate species, mainly in stands dominated by jarrah.

The first component separated three of the understorey species (*Persoonia longifolia*, *Banksia grandis* and *Allocasuarina fraseriana*) from the rest. The second principal component indicated polarization between jarrah and wandoo. The third component separated powderbark wandoo (*Eucalyptus accedens*) from the rest.

The distribution of the stands (samples) within the factor space was strongly clustered and skewed, presumably because transformation of the factor scores to square root, which tends to correct the clustering tendency, was not used. Nevertheless, Loneragan was able to draw contour lines of the Importance Value of the species within the framework. The main trend was along the second component, namely dominance of jarrah at the negative end and wandoo at the positive end. The three subordinate species (*Persoonia longifolia, Banksia grandis* and *Allocasuarina fraseriana*), declined in parallel to jarrah. Marri declined marginally from negative to positive, and was nowhere very significant. Powderbark wandoo came in near the centre of the continuum and peaked and declined rapidly. Loneragan considered the outcome of the analysis to support the earlier classification of Speck (1958), except in so far that Speck's associations were shown to be overlapping components of a continuum rather than discrete classes.

Loneragan's analysis of the understorey (shrub and herb stratum) was much less conclusive, probably because it was based on 42 most common species. It was possible to identify a connection between the ordination based on the understorey species and the two main subdivisions of the tree based classification, namely the wandoo and the jarrah-marri alliances, and between the understorey ordination and the environmental factors. The chief difficulty was in obtaining a meaningful subdivision of the understorey ordination. Similarly it proved difficult interpret the clusters derived by the PSI analysis of the understorey. The clusters had a very uneven distribution, more than half of the plots falling into one large cluster and the remainder into five small clusters. The clusters did not correspond closely to any structural or floristic classifications of Speck (1958), or to Loneragan's tree-derived clusters. Loneragan therefore concluded that the overstorey and the understorey varied fairly independently of each other.

McCutcheon 1978 and 1980

In the late seventies, McCutcheon (1978, 1980) commenced the study of the vegetation of the northern half of the Blackwood Plateau. The primary objective was to define if, and to what degree, vegetation mapping could be used in site assessment for pine plantations in that region, which at the time was covered by low quality jarrah forest. Vegetation was therefore to be studied as potential indicator of site quality, as done earlier by Havel (1968) on the Northern Swan Coastal Plain. The chief difference was that the area in which the test was to be carried out had already been surveyed by McCutcheon for soils. The methodology adopted by McCutcheon was basically that of Havel (1975a), though his plots were circular (20m radius for trees and 10m radius for shrubs and herbs). The recording was confined to 72 common species of the region, recorded on an abundance scale. The data was subjected to principal component analysis.

The first stage of the analysis produced the loadings of the species within the component space (first four components), and these were subsequently converted to component loadings for the plots.

The distribution of species within the factor space, representing the relationships of the individual one to another, resembled the patterns obtained by Havel on the Northern Coastal Plain and on the sandier soils of the Darling Plateau. In addition there were groups of species specific to the Blackwood plateau and the southern forest region.

To facilitate the delineation of vegetation types four-dimensional models of the component space were built. On the combined basis of the distribution of the species and plots within the component space six vegetation types were established. The definition of the types was made difficult by the fact that the types were obviously segments of a multi-dimensional continuum.

Ultimately, six vegetation types were defined. The choice of a such low number of types probably arose out of the low number of soil types described for the area (7). The species were then tested as to their capacity to define the vegetation types. The indicator groups formed were designed specifically to assist in soil surveys. The six vegetation types were found to be too broad to allot individual observations to them and numerous intermediate types were generated. In particular, the influence of vegetation typical of lateritic soils was found to extend, to some degree, to 47% of all sites.

The value of the study to this project is that it has established good ecological relationships for an area, in which ecological work has otherwise been at a very low level, and has provided a good, tested set of indicator species. Its chief limitation is that it drew its samples from, and was tested for its effectiveness on a relatively restricted area of 1990 ha, though its was subsequently used as an aid to site classification over a much wider area.

Beard 1979a, 1979b, 1979c and 1981

Later on the vegetation mapping on structural basis was taken up by Beard (1979a, 1979b, 1979c) who mapped the remaining regions of the southwest (Perth, Pinjarra and Albany *and* Mt. Barker) at the 1: 250,000 scale and than combined his maps and those of Smith (1972, 1973 and 1974) into the Swan Vegetation Map at 1:1,000,000 (Beard 1981). In the explanatory notes Beard went beyond structural vegetation mapping and discussed natural regions, climate, geology, geomorphology and human influences, as well as discussing vegetation plant formation, vegetation series and vegetation system level. He also explored the factors that control the distribution of plants, in particular trees. Where floristic information was available, as in the northern jarrah forest, it was incorporated into the discussion of the structural types. Beard's work also went beyond that of Smith in that he mapped not only the residual vegetation, but extrapolated potential vegetation into areas already cleared for agriculture. His structural mapping, expressed in colours, was augmented by alphanumeric annotation which identified the principal floristic components of the structural types, especially trees. The 1: 1,000,000 map sheet shares the limitations of the 1: 250,000 sheets on which it is based, namely the inability to subdivide the bulk of the forest on structural or floristic criteria.

Bettenay *et al.* 1980

Bettenay *et al.* (1980) carried out a description of the experimental catchments in the Collie Area of the South-west, Western Australia. The vegetation was mapped by using the method described by Havel (1975a and b), who delineated 21 distinct site-vegetation types in the northern jarrah forest. In small areas, such as the Collie catchments, it is possible to increase the number of types by mapping variants of the major ecosystems using a combination of coding letters which are relevant to the area. In addition to the vegetation species used by Havel, a reconnaissance of the catchments was made, and any plant species, which showed promise as an indicator of a particular ecotype was added to the booking sheet. These were assessed at the completion of the survey, and retained or discarded accordingly.

The recording and mapping of vegetation was facilitated by the survey grid, and boundaries were plotted directly on the base maps by pacing from the survey pegs, and by the use of contours. Interpretation of aerial photographs was also used for checking the boundaries of some types.

Heddle 1979 and Heddle *et al.* 1980a

Heddle (1979) and Heddle *et al.* (1980a) extended the interpretation of vegetation patterns in relation into landforms and climate the vegetation complex mapping for the Darling System (System 6 mapping). This area covers approximately a third of the south west Forest Region. In the development of this mapping technique Heddle *et al.* (1980a) re-lied on the previous studies in the area and in particular the detailed site-vegetation type work of Havel (1975a and 1975b), the Aerial Photographic Interpretation (API) mapping by the Forests Department of Western Australia, the topographic data held by the Department of Land Administration, the landform and soil mapping of Churchward and McArthur (1980) and, the previous vegetation mapping by Smith (1974) for the Collie area. The studies by Beard (1979a and 1979b) were being developed concurrently with those of Heddle *et al.* (1980a), and therefore the essentially structural formation mapping of Beard was not available to Heddle *et al.* (1980a) at the time of the latter mapping.

The concept of the vegetation complexes enabled Heddle *et al.* (1980a) to address the linkages between the detailed mapping by Havel (1975a and 1975b) and mapping at regional mapping level. It was similar to the land system approach of Christian and Stewart (1953) used in the Katherine - Darwin region.

The mapping by Heddle *et al.* (1980a) illustrated the original plant cover and attempted to describe the relationship of the site-vegetation types to the underlying landforms and soils and climatic patterns. In relation to the reliance on climatic patterns, the studies by Gentilli were relied on the interpretation of patterns of vegetation (Gentilli 1972, 1979a). All mapping was undertaken at a scale of 1:25,000 and 1:50,000, with the assumption that all line work would be reduced by a factor of 5 for the maps deliverable at a scale of 1:250,000. This necessitated some rounding off of detail for reduction purposes.

During the mapping project detailed fieldwork was undertaken in selected areas and broad reconnaissance work was undertaken over the extensive road and track system throughout the project area.

Christensen 1980

In the late 1970's, Christensen undertook a range of studies on the marsupials (*Bettongia penicillata* and *Macropus eugenii*) in the Perup forest area, east of Manjimup. Although the prime purpose of this study was to investigate the vertebrate fauna species, detailed recordings were undertaken on the vegetation and fauna habitats.

In the vegetation component of his study, he followed closely the methodology of Havel (1975a). Frequency on scale of 1-5 was recorded for 73 common and indicator species on 149 circular plots of 20m radius. The data analysis by means of principal component analysis was carried out to the stage of ordination of the species and the plots on the first four axes. He did not define vegetation types or indicator groups.

Trudgen 1984

Trudgen (1984) carried out the survey of the Westdale-Dobaderry group of reserves. The reserves cover a wide range of local topographic and edaphic features. This diversity led Trudgen to describe sixty-two vegetation types, composed of 337 species, from an area of 4005 ha. Some of these types were described using Havel's nomenclature, e.g. wandoo types Y, L and M; others as combination of Havel's types, e.g. MG, YF; or as subtypes e.g. J. and J. Number of types were described de novo, as not covered by Havel, e.g. *Banksia prionotes* open woodland; or as sufficiently different to warrant separate definition, e.g. Flooded Gum types d, e *and* f. The survey consisted of aerial photo-interpretation at scale of 1:40,000, followed examination in the field of the areas of uniform texture on the photographs, chiefly by traverses along tracks in a four wheel drive vehicle, supplemented by foot traverses. Some of the types occupied areas too small to be mapped at 1:40,000. Trudgen considered the types defined to be composed of a range of plant communities, chiefly as varied understorey under a relatively small number of dominants. Trudgen's description of the vegetation of the reserves approaches the fineness of detail of some Braun-Blanquet associations, without the labourious identification of the "faithful" species.

Trudgen's report and the earlier published studies (Havel 1975a and 1975b) were used by Campaign for Native Forests (Cahill 1984) to put forward a proposal for a very large wandoo reserve of 111,630 ha along the eastern boundary of the State Forest from Mundaring to Wandering. The proposal contained no new information relevant to classification and mapping of vegetation.

Geomorphological Mapping

Although geomorphical mapping does not strictly fit into the category of vegetation mapping, it can be an important aid to vegetation mapping, particularly in regions where floristic differences are not reflected in the structure of the vegetation and are thus not mappable from aerial photographs. This is the case in the jarrah forest, where one species is dominant over hundreds of thousands of hectares with only minor structural variation.

The importance of geomorphology in determining the soil patterns, and hence vegetation patterns, has been recognised in Western Australia for some time. The earliest of this work dates to the 1920's and 1930's (Clarke 1926, Jutson 1934), but the main relevant development began in the agricultural areas (Mulcahy *et al.* 1961), and then in the forested areas (Mulcahy *et al.* 1972, Finkl 1976). It was at this stage that the linkages between geomorphology and plant ecology were developed through mapping of vegetation over a range of geomorphic units. The geomorphological mapping was extended by McArthur *et al.* (1977) to the Murray catchment and by Churchward and McArthur (1980) to the entire forested region north of the Blackwood River.

From the early stages geomorphologists and forest ecologists interacted, chiefly with the latter utilising the maps of the former or co-operating with them (McArthur and Clifton 1975, Churchward and Batini 1975, McArthur *et al.* 1977). On occasions the forest ecologists drew attention to landforms which, on basis of their vegetation studies, warranted new landform categories, such as the Cooke landform (Havel 1975b).

McArthur and Clifton (1975) extended the geomorphological mapping to the south coast near Pemberton, dealing not only with geomorphology, but also with vegetation and land use. Their work was subsequently expanded by Churchward *et al.* (1988) to cover the bulk of the south coast from Northcliffe to Mt Manypeaks. The descriptions provided in this latter work facilitated the establishment of linkages between the geomorphology, landscape and vegetation.

Parallel to the work of the CSIRO Division of Land Resources by Mulcahy, McArthur and Churchward, the Department of Agriculture commenced the Land Resources Series, which assisted in filling in some of the gaps in geomorphological mapping. Initially the latter mapping did not include areas of State Forest. The areas mapped were the Darling Range, east of Perth (King and Wells 1990) and the Northam Region (Lantzke and Fulton 1992). In the southern region, Tille and Lantzke surveyed the Busselton - Margaret River - Augusta area in 1990. The last study of Churchward in Manjimup (1992) formed part of this series. Smolinski (1999) rationalized the Tille and Lantzke's and Churchward's maps near the Blackwood Plateau, and the largest as yet unmapped area south of the Blackwood and east of Manjimup. There have been minor differences in the approach from the CSIRO and Department of Agriculture researchers, nevertheless both approaches have provided linkages between geomorphology and vegetation which has facilitated vegetation mapping in the South-West Forest Region in Western Australia.

Site-vegetation Type Mapping for Assessment of Dieback Disease Risk

After Havel (1975b, 1979a and b) demonstrated the relationship between site-vegetation types and the occurrence of the dieback disease caused by *Phytophthora cinnamomi,* various agencies and consulting groups used site-vegetation type mapping as a means of predicting the disease risk and potential hazard. Shearer *et al.* (1987) sought to refine the most critical range of the vegetation continuum for dieback expression. The relationship between site-vegetation types and the expression of the dieback disease in the southern region was defined by Strelein (1988) and later refined by Grant and Blankendaal (1988). Extensive areas have been subsequently mapped from the point of view of dieback hazard using plant indicator species and vegetation as an aid in mapping. In this latter work the emphasis has been on the interface between the P and S site-vegetation types as defined by Havel (1975a and b) which is considered to be the best predictor of the highly susceptible (P, SP) and less susceptible sites (ST, T).

Shearer and Tippett (1980) placed an emphasis on the hydrological aspects of Havel's site-vegetation type classification, such as shedding of moisture from convex slopes and steeply dissected slopes, and the accumulation of moisture in weakly dissected landscapes with concave slopes and depressions. They also related severity of impact of the disease to the floristic composition of the particular site-vegetation types, in particular the proportion of species from the highly susceptible families, such as Proteaceae and Epacridaceae.

Havel Land Consultants 1987

Havel Land Consultants (1987) has carried out environmental impact studies for the Water Authority of Western Australia. The studies were primarily predictions of the likely impact of dam and pipeline construction, on the vegetation within State Forest and Reserves. An appropriate technology was developed for the purpose. The fieldwork consisted primarily of across-the-valley transects covering the likely areas to be inundated. The vertical reference frame, developed for the proposed engineering works, was utilised to reference all observations of vegetation and the relevant environmental factors. The data was entered into OMNIS programme and the impact determined by specifying the level of inundation for the varying engineering options. The observations were carried out along transect lines at 50m intervals and consisted of total numeration of all species on circular plots with radius varied according to the size of the vegetation component being observed, eg largest for trees and smallest for herbs. The OMNIS database made it possible to extract information on the occurrence of any individual species anywhere within the river basin studies. The main benefit, from the ecological point of view, is the strong accent on vertical distribution of the plants and of edaphic and topographic features. Because of the accent on river basins the study made up for the deficiencies of earlier studies of Havel (1975a) in which there was a bias towards the upland surfaces of the Darling Plateau.

The definition of types was carried out to a finer degree than Havel's 1975b, in that a high proportion were classified as being intermediate types. It was also found necessary to subdivide the extreme types inadequately covered by Havel classifications, that is A and especially G. All the types classified as R, G or their derivatives were subjected to additional analysis using Minimum Spanning Tree (MST) programme EM420 (program developed by E.M. Mattiske and Associates, which is based on the published work of Rohlf 1973). The programme delineated clusters, which were summarized in the form of Minimum Spanning Trees and Linkage Dendrograms.

Strelein 1988

The work of Strelein (1988) on the Darling Plateau south of the Blackwood River and on the adjacent Southern Coastal Plain had as its objective the classification of the southern jarrah forest as an aid to forest management, in particular silviculture. It also followed the methodology of Havel, to greater degree and to a further extent than that of McCutcheon (1978). The classification was not seen as an aid to soil survey, but as an objective in its own right.

The sampling was stratified on the basis geomorphological classification of McArthur and Clifton (1975). There was a tendency to link the sample plots along a transect, the degree to which this was done being determined by the variability of the sampling area. The sampling plots were circles with 20 m radius, within which the set of indicator species was assessed on the basis of cover. The tree stratum was described in detail on the basis of several silvicultural and mensurational parameters. Each plot was also sampled for soil, in form of soil profile description and a laboratory sample, which was subsequently analysed for both physical and chemical parameters.

Strelein subjected the original data set to preliminary statistical analysis using Reciprocal Averaging program RECAV (Hill 1973), which proved of limited use because it tended clump the data excessively. A locally developed program MAYHAP, which derives a matrix of V-coefficients (Krebs 1972) helped in the understanding of underlying environmental factors and assisted in the reduction of the data pool to a manageable size for the principal component analysis (PCA), which was the main statistical tool used. The program used was SPSS R-type with varimax rotations. To reduce clumping and congestion square root transformation was used. The initial output, the loadings on the components, was used to constructs a four dimensional model of the location of the various species within the component space.

Using the four-dimensional models, Strelein defined a set of site-vegetation types, which he then examined in terms of vegetation components and site attributes, using the program CORD and Discriminant Analysis from the SPSS package. He also used the same combination of programs to define the silvicultural characteristics of these types.

The chief value of this study is the meticulous way in which Strelein tested a very wide range of indicator species, both in terms of which environmental factors they reflect, and the precision with which they do it. Only a minute fraction of these analyses is actually displayed in the report, but the original computer outputs are still available.

Some of the site-vegetation types as defined by Strelein bear considerable similarity to Havel's northern site-vegetation sites and even are identified with the same letters of alphabet. In addition to the indicators that respond to edaphic factors almost irrespective of climate there are also indicators which reflect the cooler and moister climate of the southern jarrah forest. Further, there are types which bear no close resemblance to the northern types but reflect the dominance of depositional rather than erosional processes on the southern coastal plain.

Regrettably, Strelein's work was not progressed to the next stage of actually mapping areas of the southern forest to test if his types are real and to determine what part of the landscape they occupy and how extensive they are. Before leaving the research, Strelein did, however, attempt to relate his site-vegetation types to the geomorphological classification of Churchward *et al.* (1988), which was in process of development in the southern forest region at the time.

Although Strelein restricted his sampling to jarrah forest, two of his types contain small proportion of karri and provide an overlap with and link to the corresponding study of the karri forests by Inions *et al.* (1990a and 1990b). Its also links up with the classification of the southern coastal plain by Wardell-Johnson *et al.* (1989), which overlaps with it in extreme southeast.

Inions *et al.* 1990a and 1990b

The studies of Inions *et al.* (1990a and 1990b) mark the beginning of a new era in vegetation classification in southwestern Australia. In a sense Inion's work is transitional, at least in the objective, in that vegetation was still studied as a means to an end rather than an end in itself. The purpose of his study was to derive criteria for the classification of the regenerated forests of karri, for the purposes of economic management. The location of the sample plots was also management-driven, in that they corresponded to permanent inventory plots used to monitor growth of the stands. As the inventory plots were well stratified across the geographic range of karri, the linkage was not necessarily detrimental. Altogether Inion sampled 204 plots distributed over the main range of karri from south of Nannup to Irwin Inlet east of Walpole.

Inion's study also resembled earlier studies in its accent on environmental factors as well as the vegetation, in fact, it probably represents the most thorough study of this kind in Western Australian forests. The climatic data for the plots was derived by means of the Bioclimatic Prediction System of Booth *et al.* (1988) and included parameters which would not be normally available, such as radiation and evaporation, as well as seasonal variation in the more common criteria such as rainfall and temperature. The sampling of the soil parameters was also more detailed than in earlier studies, combining both superficial and deep sampling, at 10cm depth, and below.

However, it was in terms of analytical methodology that the study marked a major advance, based on corresponding advances in mathematical statistics and computer capability. The environmental parameters were standardised, a matrix of dissimilarities calculated and the polythetic agglomerative strategy using unweighted pair-group method and arithmetic averages (UPGMA) was used to impose structure to the association matrix. Other strategies employed were the space dilation favouring even-sized groups, and ordination by principal co-ordinate analysis. Separate classifications were carried out on edaphic and climatic attributes, resulting in 5 soil groups and 8 homoclimes respectively.

The soil groups ranged from relatively infertile acidic soils to the least acid soils with high fertility. The homoclimes ranged from coastal sites with high rainfall, low summer temperature and low radiation to inland sites with medium to low rainfall and higher summer temperatures, resulting in an overall drier climate. The climatic factors appeared to have a clearer effect on the performance of karri than the edaphic factors, bearing in mind that by restricting the sampling to regenerated karri stands the edaphically more favourable sites would have been selected. The less favourable sites in the region, carrying jarrah, were covered by Streleins's (1988) study.

Because of concern about the influence of plant development (succession) on the relative importance of the species within the plots, all plant data was recorded in binary form, presumably as just presence or absence. The community types were defined using agglomerative hierarchical cluster analysis, employing the Czekanowski coefficient. As in the case of the environmental parameters, an association matrix was imposed using the polythetic agglomerative strategy using unweighted pair-group method and arithmetic averages (UPGMA) was used to impose structure to the association matrix. Also used was the space dilation strategy favouring even-sized groups. Both normal (ecological tolerances) and inverse (species) analysis was carried out using the methodology and terminology of Austin and Belbin (1982). In the case of the species analysis, the TWO-STEP procedure was used to calculate the measure of similarity. Instead of defining the community types by letters as had been done in previous forest site classifications in WA, Inion used the names of prominent retired foresters. He considered the definition of the community by component species as impractical, as a number of species would be needed for each community type.

Inions defined five community groups and subdivided these into thirteen community types.

Inions provided a set of indicator species, which covered the continuum. Some of his more marginal types contained some jarrah and thus overlapped with Strelein's classification, providing a link between the two classifications, which covered a similar climatic region.

Wardell-Johnson *et al.* 1989, 1995

Although the study by Wardell-Johnson *et al.* (1989) was published slightly earlier, it is discussed after Inion *et al.* (1990a and 1990b) studies because it differs from earlier studies of southern forests not only in methodology but also in objective. Its primary objective is the study of vegetation in a National Park, for the purpose of defining sites with similar floristic composition, with the ultimate aim of protection and management of that vegetation. It shares with Inions studies the taxonomic and computational expertise, in that basically the same personnel was involved. In terms of the area studied, and in terms of climatic factors, it is little more than a small subset of the area studied by Strelein (1988) and Inion *et al.*(1990a and 1990b), but as it did not confine sampling to a particular forest formation or type, it covered a much wider edaphic and floristic range than either of these studies. In particular, it gives much better coverage of the less favourable sites, such as dunes and swamps. A total of 219 sampling sites, covering the whole of the Walpole National Park of 17986 ha, was established in 1985 and 1986. The location of the plots was based on the geomorphological studies of Churchward *et al.* (1988). The plots were large (10m x 10m) quadrats within which the species were recorded on a scale of abundance developed by Havel (1975a), from 1 for rare to 5 for species completely dominating the site. In addition soil description to the depth of 1m was also carried out. The structure of the community was described according to Smith's (1972) and Specht's (1970) terminology.

The first step in the analysis of the data was the elimination of singletons in order to reduce stochastic variation. As a next step a matrix of pairwise associations between sites was calculated using the Gower (1971) metric, supplemented by Belbin *et al.*'s (1984) programme BIGD to ensure normal distibution of the association measures. As in the case of the Inions *et al.* (1990a and 1990b) studies, an association matrix was imposed on the floristic data using the polythetic agglomerative strategy using unweighted pair-group method and arithmetic averages (UPGMA) was used to impose structure on to the association matrix. The coefficients used were such as to enforce space-dilating strategy and resist the formation of a single large group. The acceptability of the imposed groups was tested by means of Principal Co-ordinate Analysis (PCA). The species analysis, that is the classification of species by sites, was carried out by the procedure TWOSTEP, which defines groups of species with similar ecological tolerances.

The defined groups of species and suites were then merged and presented in a two-way contingency table. Species with poor power of discrimination were excluded from subsequent analysis and species with high site fidelity were identified by discriminant analysis (Fisher 1936) to maximise the separation between community types and provide the basis for the allocation of unclassified sites to defined groups.

Of the 233 species originally used in the analysis, 52 were isolated on the basis of their strong fidelity, for discriminant analysis. It was found that allocation to correct groups did not deteriorate if the data was converted to binary form, which is preferable for field use. Of the 24 sites sampled close to the original samples, 92% were classified to correct community type.

The study found a lack of congruence between floristic community types and structural data.

Subsequently Wardell-Johnson *et al.* (1995) commenced study of the forests and woodlands to the north and east of Walpole National Park, mainly east of the areas surveyed by Strelein (1988) and Inion *et al.* (1990a), though there is a degree of overlap. The region, named by Wardell-Johnson *et al.* (1995) the Tingle Mosaic after three endemic eucalypts, covers an area of 3,700 km2 along the south coast and its hinterland. It is a subset of a larger area covered by Churchward *et al.*'s (1988) landform and soil maps.

The climate in the area is quite diverse, having a gradient in annual rainfall from 750 mm in the northeast to 1400mm in the southwest. The temperatures are higher along the coast in the winter and lower in the summer, than is the case inland.

The study incorporates the floristic data of Wardell-Johnson *et al.* (1989), but additional 441 quadrats (20m x 20m) have been added. The location of the plots was based on Churchward *et al.* (1988) geomorphological maps, with preference being given to areas in existing conservation reserves rather than private property or road reserves containing relatively undisturbed vegetation. All quadrats were marked in permanently and were checked at least twice. Basal area was used as the index of the biomass of the trees. In addition to the floristic data, description was made of the site in terms of climatic variables derived from BIOCLIM, description of the topographic factors such as slope, aspect and occurrence of rock outcrops. The soil parameters recorded were the depth to a constraining layer, and substrate of the plot was described in the broad categories of granite, sandstone/siltstone, aeolian sands or none. In addition to the soil profile description obtained from a pit in the centre of the plot fifteen superficial (10 cm depth) samples were collected from 15 locations within the plot, pooled in to five composite samples and analysed for both physical and chemical properties.

The floristic data, containing 857 vascular species on 441 quadrats, was analysed by means of the cluster analysis (Czekanowski metric, UPGMA) and ordination (SSH program of PATN). The process generated five floristic community supergroups, 12 community groups and 44 community types. The supergroups were considered to be sufficiently discontinuous to require separate ordination to get higher resolution of the floristic assemblages within them. The supergroups were described as

Shrubland/woodland
Dune
Swamp and outcrop
Open forest
Tall open forest.

The diagram showing the clustering process was terminated at 44 community types which appear to be well defined, but the floristic data was reported at the level of 12 community groups. All community types were described in terms of their broad climatic and edaphic parameters, and in terms of floristic richness. They ranged from tall open forest of karri and tingle to coastal herblands in terms of height, and from swamps to rock outcrops in terms of site.

Tabulation of the areas covered by the various geomorphic units within the study area was also given, as was a complete ennumeration of species within the study as a whole, and within the twelve community groups. Some of the community groups are too broadly defined, in particular the group containing wandoo woodland and outcrop, which consists of 11 quite heterogeneous types.

It would appear from this that in a large data set the definition of groups cannot be left entirely to computer programs and simple numerical rules. The termination of the clustering process which was appropriate to the forest groups was inappropriate to the more extreme sites. The highest level clustering, at the level of supergroups, appears to have generated only two truly homogeneous groups, those of the open forest and tall open forest.

Mattiske and Burbidge 1991

Mattiske and Burbidge established a series of permanent sites in the John Forrest National Park and the Red Hill area as part of a wider series of biogeographical studies for the Department of Conservation and Land Management (Mattiske and Burbidge 1991). The project, within the John Forrest National Park and Red Hill area was funded by the Heritage Council of Western Australia. The sites were selected by Mattiske and Koch on the basis of the dominant site-vegetation types as defined by Havel (1975a and b) within the John Forrest National Park and were intended to provide a long term monitoring baseline.

Smith 1994

Relatively little was done in the field of vegetation mapping on the Blackwood Plateau until the study by Smith (1994) on two rare *Chamelaucium* species. Smith (1994) attempted to use McCutcheon's (1978) classification as ecological reference, but found that some of the areas in which he was working were more dissected and more fertile than any of the types described by McCutcheon and that they could in fact be better described by Strelein's (1988) classification of the adjacent crystalline Darling Plateau. Smith felt that additional vegetation classification and mapping was needed on the Blackwood Plateau. Smith also surveyed a small conservation reserve near Margaret River township, west of the Blackwood Plateau.

E.M. Mattiske and Associates, Mattiske Consulting Pty Ltd 1979 to 2000

E.M. Mattiske and Associates and Mattiske Consulting Pty Ltd (1979 to 2000) have carried out extensive vegetation assessments and vegetation mapping projects for a range of mining companies and government agencies, and in particular Alcoa of Australia Limited and Worsley Alumina Pty Ltd, operating in the south west forest region. The data collected includes detailed measurements in established vegetation plots (20m x 20m and 40m x 40m) and extensive vegetation mapping on various grid systems (60m x 120m; 120m x 120m; 200m x 100m). The data collected for a range of common and indicator species on the various grid systems was based on the ranking scale of 1 to 5 (as developed by Havel 1975a) within a 5 metre radius for the understorey species and within a 20m radius for overstorey species. Data has been collected in some 180 permanent vegetation plots and at more than 25,000 mapping sites to date and has been analysed in various ways, although only 18,000 of these sites were used in the RFA vegetation mapping project. Each project area has been mapped at a scale of 1:10,000 using the site-vegetation type system as developed earlier by Havel (1975a and 1975b). In most areas it has been possible to further subdivide the site-vegetation types to a higher level of definition (for example, the previously broad S site-vegetation type which occurs on well-drained lateritic gravel areas on the mid to upper slopes has been subdivided into ST, SP and SW and the broad G site-vegetation type which occurs on areas associated with shallow soils over granitic outcrops has been subdivided into G1, G2, G3 and G4 for mapping in the eastern areas). This further subdivision has been made on the basis of structural differences (particularly for woodland, shrubland and herbfields on extreme sites such as the G type) and floristic differences (particularly for types with more subtle soil moisture and composition changes). Many of these subdivisions have been critical in operational decisions such as hygiene management for forest diseases. In addition, several new types have been defined and includes the X type which is dominated by *Eucalyptus rudis* (flooded gum) woodland over *Melaleuca incana* subsp. *incana* (formerly *Melaleuca polygaloides*) and *Acacia saligna* on the fine particle clay soils in the eastern Yarragil and Pindalup valley systems as defined by Churchward and McArthur (1980). The latter reflects the wider coverage of the studies by Mattiske and her team throughout the northern and eastern jarrah forests. Some of the studies have been published covered under the name of the sponsors, such as Worsley Alumina Pty Ltd (1985, 1999).

In recent years, further vegetation mapping has been undertaken in the southern coastal areas. For example, within Scott National Park, Mattiske Consulting Pty Ltd (1996) described a total of 21 plant communities and grouped these into 8 groups ranging from Sedgelands to Open Forest. Many of the species groupings recorded by Mattiske Consulting Pty Ltd are similar to those recorded on coastal plain north of Perth by Havel (1968), but in addition there are many species with southern affinities recorded by Wardell-Johnson *et al.* (1989, 1995). Some of the communities developed on shallow sands over iron pans, were quite unique, with a high proportion of endemics and rare species. Overall the vegetation communities reflected predominance of swampy condition, rather like some of the coastal plains reported by Wardell-Johnson from the vicinity of Walpole.

Griffin 1992

Griffin (1992) undertook a detailed study of vegetation within the region immediately to the north of System 6, with some degree of geographical overlap. It covered an elongated north-south rectangle from Moora in the north to Chittering in the south. Whilst only the southern third of Griffin's study (Julimar and Bindoon districts) is relevant to this project, the study is important in that it covers the northern and eastern margin of many species. It has as its objective, to identify the full range of floristic variation within the region which is, on one hand, floristically very rich, but on the other hand, has been strongly affected by agricultural activities over the past century. The survey is thus basically the survey of remnant vegetation. The region has a totally inadequate system of reserves except in the extreme southeast. It overlaps to certain degree with the region studied by Loneragan (1978).

Griffin (1992) sampled quadrats of 100 m^2, which he regarded as releves (plant list), for which he recorded all species by the estimate of the canopy cover based on the Domin-Krajina Cover Abundance Scale (Mueller-Dombois *and* Ellenberg 1974). He also recorded the vegetation structure in terms of Muir's (1977a and 1977b) classification and the relevant topographic and edaphic information. Altogether he collected 479 releves, scattered in clusters throughout the region, mainly but not exclusively on reserves. These he incorporated into a database, which he analysed by means of a package of programs called PATN (Belbin 1987a and 1987b). He used the programs for three basic functions:

a) to produce groups of releves according to their species composition, and hence define floristic types
b) to identify differences between types, to hypothesise about them and to test them
c) to display the results.

The programs used were ASO (similarity measures between releves - rows), FUSE (combination of rows into groups), DEND (display of the progress of fusion), KYST (multi-dimensional ordination program), MST and TWAY (other data display programs). Initially Griffin chose 35 groups of releves which he decided to recognise as distinct vegetation types, with the provision of subdividing these further into sub-types or variants. Ultimately he arrived at 45 groups. In deciding on the groupings, he was influenced constancy and fidelity of the species.

He also attempted to produce an ordination diagram, which would summarise the information in few dimensions, but even with 15 vectors the level of "stress" was considered to be excessive and the technique was abandoned because of the extreme heterogeneity of the data. Instead Griffin displayed the outcome of the analysis in the form of a minimum spanning tree, showing the relationships between the vegetation types.

Within the area covered by the RFA study, he identified 25 groups, most of which occurred in both Julimar and Bindoon districts, but some were specific to Julimar (sand and swamp types) and some to Bindoon (rock outcrop types), which reflects the respective degree of dissection of the two regions. The largest groupings were those identified with woodland dominants (jarrah with 40 releves, wandoo with 85 releves and powderbark wandoo with 32 releves). These correspond broadly to Loneragan's (1978) dominance types, and are broader than Havel's (1975a and 1975b) site-vegetation types. However, the precision of definition is much greater for the numerous sub-types into which the large groups have been subdivided. On the more extreme sites, such as swamps and rock outcrops, Griffin has arrived at much more finely defined groups than those of Havel, complete with their "faithful" species and almost reminiscent of the Zurich-Montpellier (Braun-Blanquet) classification of southern and central Europe. Corresponding sites would not have been sampled by Loneragan.

Ecologia Environmental Consultants 1994

The central part of the proposed wandoo reserve (Cahill 1984) was, surveyed by Ecologia Environmental Consultants (1994), who established fifty-four (10m x 10m) quadrats and recorded 413 species over an area of 111,630 ha. The area surveyed overlapped with that studied by Loneragan (1978) and partially with that of Havel (1975 a and b). The area surveyed by Trudgen (1984) was a subset (3.5%) of it.

The species by site presence/absence matrix was analysed by Bray-Curtis dissimilarity measure for sites, the two-step dissimilarity measure for species and UPGMA clustering routine for both site and species (Belbin 1989). Semi-strong Hybrid Scaling was used to produce an ordination analysis using four dimensions (Belbin 1991). On the basis of the UPGMA clustering six community types were described. Of these, one consisted of one site only. The types were described in terms of the component species, enumerated by structural layers and by description of the average physical site characteristics. The community types can be related through the dominant stratum to Loneragan's sub-formations, and through both dominants and understorey species to Havel's wandoo site-vegetation types Y, M and L, to the rock outcrop type G and the swamp type AY. One of the types, dominated by *Eucalyptus accedens*, has no near equivalent among Havel's types, though it does have a close equivalent among Loneragan's sub-formations. Ecologia did not attempt such comparisons, though it reviewed Trudgen's survey and considered the disparity in the number of types defined to Trudgen's use of unbounded sites and opportunistic collecting, as well as inclusion of non-wandoo types.

Gibson *et al.* (1994)

Gibson *et al.* (1994) carried out a floristic survey of the Southern Swan Coastal Plain, which is marginally included in the periphery of the RFA project area. The purpose of the survey was to provide a more detailed knowledge of the conservation status of species and communities in remnant vegetation in the highly modified landscape. The survey involved the establishment of 509 quadrats (10m x 10m), largely located in remnant vegetation on publicly owned (Crown) land, which were intended to cover the geographical, geomorphological and floristic variation of Crown lands. All vascular plants were recorded, as well as information on slope aspect, vegetation structure and condition.

The classification process for sites utilised the Czckanowski coefficient and "unweighted pair-group mean average" fusion method (UPMGA, Sneath and Sokal, 1973). Species were classified into groups according to their occurrence on the same sites by using the TWOSTEP similarity algorithm (Austin and Belbin 1982) followed by UPGMA fusion. In addition semi-strong hybrid (ssh) ordination of the site data was used to explore spatial relationships between groups and to relate the groups to environmental factors.

The nomenclature used is based solely on floristic composition, and comprises 4 supergroups, which reflect landscape scale pattern, and 30 community types. The data pool contained 1485 species of flowering plants, of which 172 were weeds. Of the 1313 native taxa, at least 130 were as yet undescribed. The study also explored endemism, geographic range of taxa and rarity. Many of the species were recorded only once (singletons) and were not utilised in the analysis.

Gibson (1997 unpublished)

The most recent study of the southern vegetation is that of Gibson (pers. com), who has done an extensive study of plant communities along the southwestern coast, comprising 300 sites. The study has generated 30 groups. Some of the groups are geographically compact, others are spread all along the coastline from Meelup to Albany. The study has deliberately avoided the forest vegetation types, considered to have been largely covered by earlier studies. Some of the types described are similar, in broad description, to those described in the Wardell-Johnson studies (Wardell-Johnson *et al.* 1989, 1995). The early stages of the analysis have been made available to us, and are utilised in subsequent chapters.

Hopkins 1999

Hopkins (1999) and his colleagues have captured the earlier work by Beard in Western Australia in a Geographic Information System and associated Relational Database Management System. All the linework and descriptive detail was captured from the original working drawings, where these were available, or from published maps, all at a scale of 1:250,000. As part of this work there has been a rationalisation of boundaries and groupings for the production of the new 1:3,000,000 vegetation map for the entire State of Western Australia. In preparing a map at this scale the South-West Forest Region has been covered in very broad terms, however this work places the vegetation mapping project in the wider State context and biogeographical context which is relevant for its wider assessment.

Mattiske for Alcoa of Australia Limited (1979 to 2000)

Alcoa of Australia Limited has financed a number of vegetation studies in the areas mined by them. The studies were primarily located in the areas at Jarrahdale, Huntly and Willowdale in the higher rainfall areas of the western section of the Darling Ranges and in the Hedges area near Boddington in the lower rainfall areas of the eastern section of the Darling Ranges (E.M. Mattiske and Associates 1979 to 1994; Mattiske Consultkng Pty Ltd 1994 to 2000).

The vegetation data collected for these projects was either based on a 60m x 60m grid pattern, or a 120m x 120m grid pattern with detailed recordings on species, abundance of species (using the ranking system based on Havel 1975a) and a series of permanent vegetation monitoring plots established in a range of locations at all the operations.

Mattiske and her team have been able to extend the earlier work of Havel (1975a and 1975b) to include a range of additional site-vegetation types to cover the local variation across the geographical range from the western Darling Ranges to the eastern Darling Ranges. The majority of these additional site-vegetation types have been recorded within the broader site-vegetation types of S and H on the upper slopes and ridges where the soil profiles have varied from sandy-gravels to deep gravels with the resultant changes in the floristic components of the site-vegetation types.

Matttiske has also subdivided the site-vegetation types on the extreme site conditions, such as swamps and outcropping areas by utilizing the code as developed by Havel (1975a and b) and by the addition of another letter (eg. H type over shallow soils has been mapped as HG as both the H and G type indicators are present in the understorey). In areas where the structure and floristics of the site-vegetation types differ substantially from one area to another the mapping has included a combination of the code as developed by Havel (1975a and 1975b) as well as a number 1, 2 or 3. For example, in some areas the vegetation on the resulting shallow soils was coded as G1, G2 and G3.

The project areas have been mapped at the scale of 1:10,000.

Mattiske for Worsley Alumina Pty Ltd (1981, 1985, 1999)

Worsley Alumina Pty Ltd has commissioned Mattiske Consulting Pty Ltd to undertake a series of vegetation studies in the areas mined by them. The studies were primarily located in the catchment of the Murray River and its tributaries near the eastern boundary of the Jarrah Bioregion, midway between its northern and southern extremities. There is also extension towards south west of the Jarrah Bioregion along an overland conveyor to the refinery. The initial studies, Phase One Flora and Fauna Studies (Worsley Alumina *and* Dames and Moore (1981) primarily amounted to mapping of vegetation.

In Phase Two (Worsley Alumina 1985) this initial work was expanded in order to improve floristic information and definition of plant communities by Mattiske and her team to supplement it with phenological and plant dynamics information for rehabilitation after mining. The Phase Two studies involved 84 40m x 40m plots, for which the following parameters were obtained: height, basal area and number of tree stems for the plot as a whole and foliage cover of understorey species on four 5m x 5m quadrats located at the corners of the plot. Several quantitative analyses were carried out, including Carlson Clustering, Minimum Spanning Tree and Principal Axes Ordination of Plots (Q-mode) and Association Analysis, Minimum Spanning Tree, Pearson Correlation and Factor Analysis of species (R-mode).

Dendrogram summarising Carlson Clustering separated the jarrah (*Eucalyptus marginata*) forest from high rainfall refinery site and conveyor corridor from the jarrah forest from the lower rainfall mining area, and from the wandoo (*Eucalyptus wandoo*) woodland and heaths. The jarrah forest / woodland from the lower rainfall was further subdivided, mainly on topographical position and soils, as were the heaths. The Minimum Spanning Tree for jarrah forest woodland in the low rainfall zone subdivided this large group primarily on topographical position and soil texture.

The Principal Axes Ordination separated the heath plots from the rest and apart from minor overlap also separated high and low rainfall jarrah forest and woodland from each other.

Constellation diagram of associated plant species in the jarrah communities delineated several species groups, some of which resemble Havel's (1975a) indicator groups, such as *Persoonia longifolia* and *Banksia grandis* (Havel's GRAMED) and *Leucopogon capitellatus, Macrozamia riedlei* and *Phyllanthus calycinus* (Havel's FREGRA).

The constellation diagram of associated species of the wandoo (*Eucalyptus wandoo*) woodland and heath communities delineated some species groups not identified by Havel, such as *Leucopogon capitellatus, Calothamnus quadrifidus, Dodoaea ceratocarpa, Astroloma epacridis, Grevillea bipinnatifida, Trymalium ledifolium, Acacia alata, Hypocalymma angustifolium*, from heath on shallow soils of upper slopes and ridges. Ultimately six jarrah community types, three heath types, one wandoo and one rock sheoak (*Allocasuarina huegeliana*) type were delineated in terms of the component species, topographical position and soil, such as:

19JSd -open forest of *Eucalyptus marginata* and *Corymbia calophylla* with second storey of *Banksia grandis, Allocasuarina fraseriana* and *Dryandra sessilis* on gravelly soils overlying shallow rocks on ridges and upper slopes. Indicator species were *Stylidium dichotomum, Clematis pubescens, Acacia celastrifolia, Senecio leucoglossus* and *Xanthosia atkinsoniana*. The type was identified as eastern variant of Havel's (1975a) types S and T.

A matrix of species / plots was developed and the project area was mapped at the scale of 1:10,000. This was reduced to 1:20,000 for publication.

Subsequently, Worsley Alumina Pty Ltd (1999) carried out a vegetation survey of a new project (gold mine), located west of the alumina mine. In this case, detailed sampling of eight 40m x 40m plots was combined with a vegetation survey on a 50m x 100m grid published at the scale of 1:33,000. Greater emphasis was placed on relating the vegetation to landforms and vegetation complexes (Heddle *et al.*, 1980). The vegetation types were defined in terms of Havel (1975a *and* b) nomenclature, with reference to nomenclature used in earlier Worsley Alumina studies, eg ST (formerly coded as 19JSd). The vegetation types were again described in terms of over storey and second storey trees, and those understorey species considered to have indicator value. New types, not adequately covered by Havel were defined for the more extreme sites (AX riparian woodland and G3 and G4 heaths on shallow soils).

Review of Methodology for Mapping at Bioregion Scale

Local

Perhaps the most important issue that has to be decided upon is what is the form of vegetation of south estern Australia – is it composed of discrete categories, or is it a continuum? The answer to this, if it can be found, will influence the approach to the integration the earlier vegetation classifications in the region and to developing the model for mapping the vegetation. It is an issue that had to be addressed by all of those who attempted to classify or map the vegetation in the past.

The early studies (Diels 1906; Gardner 1923, 1928) tended to be based on the assumption that vegetation is divisible into discrete categories and because of the coarseness of scale the issue did not have to be addressed. Even so, Diels introduced the concept of swamp complex for vegetation not divisible at the scale that he was working at.

The first detailed studies, those of Williams (1932, 1945) defined associations and consociations, which again imply divisibility. The areas mapped by Williams were strongly dissected and the mapping was done in fine detail, which would favour the detection of discrete categories, yet Williams concluded that the units were too heterogoneous to be described as associations in the narrow sense.

Speck (1958) in his survey of the northern part of the Jarrah bioregion and its northern neighbours described three formations, 24 subformations and 62 associations using Beadle and Costin's (1952) terminology. He rejected Diel's (1906) swamp complex concept, but one of his illustrations, that of a xerosere originating from a granitic outcrop, depicted a continuum from lichens to forest. Vegetation continuity was also implied in the arrangement of his associations into a climatic series along a gradient of decreasing rainfall. For broadscale description of the region he employed the land system concept of Christian and Stewart (1952), which implies recurrent patterns of landforms and vegetation.

Lange (1960) considered the 500mm isohyet to be a significant marker for the distribution of tree species on the Darling Plateau in the Narrogin district, which midway along the eastern boundary of the Jarrah bioregion. The tree species dominant east of it had mainly inland distribution patterns, whereas those dominant west of it had mainly coastal distribution patterns. However, he also identified a group of tree species that straddled the 500mm isohyet and overlapped the distribution ranges of the first two groups.

Churchill (1961) considered the vegetation of southwestern Australia to be a continuum primarily determined by rainfall, in which each species occupied a distinct segment. However, Havel (1975a) found that the individual species could be grouped on the basis of the distribution maps provided by Churchill into small groups of species with similar distribution patterns.

Havel (1968) found principal component analysis (factor analysis) of Goodall (1954) and Pogrebnyak's (1955) edaphic net to be the most useful methods for the study of coastal plain vegetation. Havel (1975a) then extendced this approach into the Darling Plateau where he used methods applicable to both continuum and discrete categories to study the vegetation of the Darling Plateau (northern jarrah forest), and found the principal component analysis, which implies the former, more useful than the nonthetic divisive association analysis (Williams and Lambert 1959, Lance and Williams 1958). The polythetic agglomerative analysis (Lance and Williams 1967) gave outcomes that were more comparable to those of principal component analysis than the outcomes of the divisive monothetic analysis. However, Havel found it necessary to use indicator or keystone species with proven responsiveness to mathematically derived components in order to be able to divide the multi-dimensional vegetation continuum into segments that could be mapped at a local scale.

Loneragan (1978) specifically set out to establish whether the vegetation of the Darling Plateau could be objectively subdivided by statistical methods. His study area overlapped partially with that of Havel, and straddled one of the strongest environmental and floristic gradients in the Jarrah bioregion, between the jarrah (*Eucalyptus marginata*) forest and wandoo (*Eucalyptus wandoo*) woodland. Unlike Havel, he utilised only common species. By using principal component analysis and correlation analysis he was able to relate the tree data to rainfall and silt and clay fraction of the soil. He was also able to group the tree data into identifiable clusters using Goodall's Probabilistic Similarity Index (PSI), but his analysis of the common understorey species was much less conclusive, more than half of the species falling into just one cluster derived by the PSI analysis. The clustering did not relate closely to the clusters derived by the PSI analysis of the tree data. Given that his analysis was more objective than that of Havel (1975a), it indicates that the vegetation of the Jarrah bioregion is closer to a continuum that a set of discrete categories. By using less common species with greater discriminatory power Havel was able to divide that continuum into meaningful segments. Neither author was able to define discrete ecological groupings.

McCutcheon (1978, Christensen (1980) and Strelein (1988), who utilised the same methodology as Havel (1975a) in different portions of the southern jarrah forest (Warren bioregion), also described continua rather than discrete categories. However, by emphasizing species with proven responsiveness they were able to break up the continua into meaningful segments, many of which were quite similar to those derived by Havel.

Most of the more recent ecological studies of southwestern forests (Inions 1990a and b, Wardell-Johnson *et al.* 1989 and 1995) have used the polythetic agglomerative strategy with unweighted pair-group and arithmetic averages (UPGMA) in combination with ordination of the resulting site groups by principal component analysis. Although the categories are defined more objectively by this means that in the case of the earlier studies, they unmistakably form multi-dimensional continua with considerable overlap of characteristic species. This is particularly apparent in Inions (1990b) study of the regenerated karri stands, where the floristically derived site groups are ordinated on three environmental criteria (phosphorus in the soil A-horizon and precipitation and radiation in the driest quarter) to give one major trend from infertile soils in a moist and cool coastal climate to fertile soils in a warm and dry inland climate. In light of these findings, a lumpy multi-dimensional continuum, divisible by use of responsive species into workable segments, appears to be a reasonable model to adopt for the mapping of the combined Jarrah and Warren bioregions.

Loneragan's analysis of the understorey (shrub and herb stratum) was much less conclusive, probably because it was based on 42 most common species. It was possible to identify a connection between the ordination based on the understorey species and the two main subdivisions of the tree based classification, namely the wandoo and the jarrah-marri alliances, and between the understorey ordination and the environmental factors. The chief difficulty was in obtaining a meaningful subdivision of the understorey ordination. Similarly it proved difficult interpret the clusters derived by the PSI analysis of the understorey. The clusters had a very uneven distribution, more than half of the plots falling into one large cluster and the remainder into five small clusters. The clusters did not correspond closely to any structural or floristic classifications of Speck (1958), or to

Loneragan's tree-derived clusters. Loneragan therefore concluded that the overstorey and the understorey varied fairly independently of each other.

It is possible to relate some of the features of Loneragan's ordination and some of the clusters of his classification of the understorey species to Havel's broad indicator groups, as they share a few species. However, the bulk of the species used by Loneragan were rejected by Havel on the basis of preliminary analysis as being of limited use as indicators. Similarly, the bulk of Havel's indicators would have failed to pass Loneragan's criterion of commonness. Those broad indicators shared by the two authors, such as *Hakea lissocarpha* and *Lepidosperma squamatum* (formerly *Lepidosperma angustatum*), show similar trends in relation to trees and environmental factors.

Mattiske and her team have tested and developed the system (1975a and b) into a range of areas from Collie in the south, to the Julimar forest block in the north, from the Darling Scarp in the west and the wheatbelt in the east. Mattiske (1979 to 2000) has confirmed the earlier observations of authors such as Diels (1906) where vegetation mapping boundaries near extreme sites such as swamps or granite outcrops can be clearly distinguished on the basis of structure and floristics. The latter clear distinction is related to the rapid and clear changes in underlying site conditions from seasonal water-logging conditions or exposed or shallow outcropping. Mattiske has also defined and mapped a range of site-vegetation types which are a refinement of the earlier system developed by Havel (1975a and 1975b). The main issue that has arisen from these local vegetation mapping projects are that it is possible to subdivide and map the vegetation, however within the forest continnum it is necessary to rely on different indicators or keystone species in different zones of the northern jarrah forest as different species have varying tolerances to underlying landforms, soils and climate conditions. To illustrate the latter point, The site-vegetation type P as defined by Havel (1975a) was based on his sites within the Jarrahdale and Dwellingup areas where some of the key indicators included the overstorey species – *Allocasuarina fraseriana* (sheoak, formerly known as *Casuarina fraseriana*), *Eucalyptus marginata* (jarrah), *Banksia grandis* (bull banksia) and *Persoonia longifolia* (snottygobble) and the understorey species such as *Adenanthos barbiger and Grevillea wilsonii*. Although the overstorey species persist across the occurrence of this site-vegetation type (although the subspecies of jarrah changes in the northern and eastern sections of the northern jarrah forest from *Eucalypstu marginata* subsp. *marginata* to *Eucalyptus marginata* subsp. *thalassica*), the occurrence of the understorey species vary and *Grevillea wilsonii* is relatively confined to the higher rainfall areas. Therefore the *Grevillea wilsonii* whilst a critical indicator species for this site-vegetation type near Jarrahdale and Dwellingup in both drier eastern forest areas and in the coller southern forest areas near Collie this species is not as reliable as *Adenanthos barbiger*. Consequently, the site-vegetation types not only reflect the local subtle changes in the underlying site conditions but also the overarching subregional subtle changes in landforms, soils and climate. The latter variation has been reflected in mapping the broad P as defined by Havel (1975a and b) into a series of site-vegetation types where the continuum between P and S has been further subdivided into P, SP, PS and S depending on the indicator species and their reponse to the local and regional changes in conditions.

National

As the Regional Forest Agreement process in WA commenced whilst the same processes were well under way in Victoria and Tasmania. The authors compared the applicability of the methodology of vegetation mapping used in these latter areas to the south western Australia.

In Tasmania, there was a high degree of edaphic and topographic diversity and a high degree of floristic diversity of the dominant tree stratum, as compared to southwestern Australia. These features made the dominance classification the logical choice for vegetation mapping in that state

(Tasmanian Public Land Use Commission, 1997), but questioned its applicability to southwestern Australia, where topography is relatively subdued, edaphic differences subtle and extensive areas are dominated by just one or two overstorey species, though the shrub and herb storey is rich and floristically diverse. The Tasmanian map depicts extant forest types and gives no information on other non-arboreal structural types such as heaths and shrublands.

In Victoria, the forested areas were subdivided into forest types and ecological vegetation classes. The latter incorporate the description of the vegetation structure (forest, woodland, shrubland, heath), the nature of the understorey (heathy woodland, grassy woodland) and the underlying environmental conditions (montane dry woodland, floodplain riparian woodland). The definitions also recognised the fact that at the scale of mapping adopted (1: 250,000) the diversity may be such as to make the mapping of homogeneous categories impossible, and consequently many of the categories are described as mosaics or complexes of two or more vegetation types (rocky outcrop shrubland/herbland mosaic, valley grassy forest/box ironbark forest complex). The ecological vegetation classes may consist of two or more floristic vegetation communities, and both categories are, wherever possible, defined by reference to the original ecological studies, such as "Limestone Box Forest (Woodgate *et al.*, 1994)".

The vegetation mapping project for the Victorian RFA process covered both the extant vegetation and pre-1750 vegetation. The latter was compiled by extrapolation from the former, with reference to land systems and geology and using expert opinion on the influence of landform, soil, climate and hydrology on the development of ecological vegetation complexes.

From many aspects, the Victorian approach appears to be more applicable to southwestern Australia than the Tasmanian approach, though there are some differences. In terms of topographic and edaphic diversity of the landscape and floristic diversity of the forest overstorey, Victoria appears to be closer to Tasmania than to Western Australia. Judging from documentation of past vegetation classifications, there is a better coverage and fewer gaps in Victoria than in Western Australia, which is to be expected given earlier and denser European settlement and smaller total area. This provided a better basis for the Victorian mapping project compared to the Western Australian one. On the other hand, the landform mapping coverage appeared to be as wider and more comprehensive in Western Australia, which is important given the high degree of interpolation and extrapolation that will be needed to obtain full coverage there.

International (Canada, USA)

The development of appropriate methodology for extrapolation from existing classifications and maps is therefore a key task. At the commencement of this project the scheme being developed for British Columbia by Pojar *et al.*'s (1987) appeared to be most relevant, and was adopted as a prototype. The essence of this approach was to bring together all earlier synecological work done in the province into an overall scheme, which is essentially what was attempted in the south western forested areas of Western Australia.

Although the past synecological studies in British Columbia have been broadly based on Braun-Blanquet's approach, the specific methodology developed by Krajina (1960) and his associates such as Pojar, Meidinger and Klinka is less rigid than the European school, in that it utilises environmental data and does not insist on the narrow definition of faithful and character species. It is in fact considered by Pojar *et al.*'s (1987) to be a synthesis of several traditionnof ecological classifications, including in addition to the Southern European tradition of (Braun-Blanquet, Ellenberg) the Russian (Sukachev, Pogebnyak), Northern European, British and North American (Whittaker, Daubenmire, Hills, Barnes). The principal concept is that the proper subject of vegetation studies is the biogeocoenose or ecosystem, defined as the sum of vegetation, animals and abiotic factors of the environment (climate, soil moisture and soil nutrients). Other concepts in the classification scheme are that regional, long-term climate is the fundamental determinant of the nature of terrestrial ecosystems, and that beside the climatic climax there are other climaxes such as edaphic, topoedaphic, zootic and fire climaxes. In the case of fire succession, the seral stands usually show definite successional trends which can be predicted, and understorey vegetation can be used as an indicator of these trends, and hence of the potential natural vegetation of a site. A particular emphasis is put on the principle of equivalence, namely that sites with same or equivalent properties have the same vegetation potential.

The factors of the physical environment are not always physically measured but are rated according to scales considered to reflect the biological effect of these factors. For instance, the soil moisture regime, defined as the average amount of soil water annually available for evaporation by vascular plants, is rated on a scale from very xeric (0) to hydric (8), which is developed by synthesis of soil properties and indicator plants. On this scale, the basic divisions are are based on whether there is groundwater in the rooting zone during the growing season (6-8) or not (0-5) and whether a soil water deficit (0-3) occurs or not (4-5). The sites with soil water deficit are rated according to the length of the water deficit period, from excessively dry (0) for over 5 months of drought to slightly dry (3) for less than 1.5 months of drought. For sites with groundwater in the rooting zone the critical factor is the depth to groundwater table, rated as very moist (6) if more than 30 cm, wet (7) if below the surface) and very wet (8) if above the surface. A key for identification of potential soil moisture regimes has been developed.

Similarly the soil nutrient regime is defined as the amount of essential nutrients available to vascular plants in long term, which is a measure that is difficult to determine quantitatively because it is influenced by many other factors of the environment. For routine work a scale of five classes (A-B), derived by subjective synthesis of soil properties and indicator plants is used. In the case of British Columbia, an attempt was made to relate measurable properties of the soil, such as pH, C/N, total N and SEB (sum of exchangeable Ca, K and Mg) to floristic composition and productivity of forest stands. The range in one experimental study was from pH of 3.8 and C/N ratio of 73 for very poor (A) to pH of 5.0 and C/N ratio of 21 for very rich (E) site.

The soil moisture and soil nutrient scales are combined into an edatopic grid, a concept first developed by Pogrebnyak (1930). In Pojar *et al.*'s (1987) scheme the edatopic grid is a 9x5 matrix. Pogrebnyak's concept of edatophic grid has been used locally by Havel (1968).

Similarly, climate rating in Pojar *et al.*'s (1987) scheme is not simply based on measurement of climatic data, which often are not available or are difficult to define and measure, but on the zonal ecosystem concept and on observation of the vegetation. A zonal ecosystem is one in which the integrated influence of climate on the vegetation and the soil is most strongly expressed, that is one with intermediate light, heat, soil moisture and soil nutrients. This is interpreted as mid- to upper slope position, gentle to moderate slope and moderately deep to deep loamy soil without an impeding horizon.

It is in the description and classification of vegetation that Pojar *et al.*'s (1987) classification scheme is closest to that of Braun-Blanquet (1964), namely in the hierarchy of categories (class, order, alliance, association, sub-association), formal nomenclature (endings such as –etea, -etalia, -ion, -etum and –etosum), the use of diagnostic plant species (character, differential, companion and accidental) and analysis by means of diagnostic tables.

It is not proposed to go into details of this as the applicability of Braun-Blanquet (1964) to Australian conditions has already been tested by Bridgewater (1981), who concluded that the acceptance of some of its features, such as the nomenclature, is unlikely, but that the system has merits that have not been given adequate recognition. The positive aspects of the Braun-Blanquet system identified by Bridgewater were:

a) the products of the process are efficient mapping units
b) it has a low technology requirement
c) it is a polythetic process in which all species are used to produce the classification
d) the species remain untransformed at the end of the process
e) the final classification has a high predictive value if the autecology of the component species is known.

The chief problem in applying Pojar *et al.*'s (1987) approach locally is that the hundreds of man-years already invested in forest synecology in British Columbia cannot be matched, and that their implicit assumption about the homogeneity of vegetation types go against some significant studies in Western Australia, such as those of Loneragan (1978) and Churchill (1961, 1968). In addition, British Columbia has a much greater topographic range, and yet is floristically much poorer, than southwestern Australia.

An even more significant counter-indicator against adopting Pojar *et al.*'s (1987) methodology uncritically is that even in British Columbia a purely biogeoclimatic approach appears to have been recently abandoned in favour of a more broadly based ecosystem mapping (Banner *et al.*, 1996), which combines the biogeoclimatic ecosystem classification and ecoregion classification. The new combined approach utilizes ecoregions and biogeoclimatic zones to stratify the landscape into broad units that are physiographically and climatically homogeneous. Within this broad framework permanent landscape units are then delineated on the basis of terrain features. Within these are nested ecosystem units, derived from the site series of the biogeoclimatic ecosystem classification. The concept of zonal site, that is site with intermediate moisture and nutrient conditions and thus best reflecting the regional climate, which is central to the biogeoclimatic classification, is retained. The ecosystem units are the lowest level mapping individuals, which reflect the moisture and nutrient regimes and the climax vegetation potential of the site. Provision is made for recognition of more detailed variation in topography and soils, by means of site modifiers. There is also provision for variation in stand development with time in structural stage and seral association modifiers.

It is significant that whereas ecoregion units are mapped at the relatively small scales of 1:250,000 to 1:2,000,000, the detailed site- or vegetation community mapping is normally carried out at the much larger scales of 1;5,000 to 1;10,000. Intermediate ecosystem (habitat) maps at scales of 1:10,000 to 1:50,000 have also been produced for research and planning purposes.

On the basis of definition and scale the Jarrah and Warren bioregions correspond to Canadian ecoregions. There is not an exact equivalence between the proposed climatic zones based on Gentilli's (1989) bioclimatic studies of southwestern forests and the biogeoclimatic zones and subzones used by Banner *et al.* (1996) in British Columbia. Whereas in British Columbia temperature regimes, determined by latitude, altitude and continentality, are the key determinants, in southwestern forests the temperature is a relatively minor factor compared to moisture balance. It is likely that the climatic zones used in this study are more equivalent to Canadian subzones. They are viewed more as semi-continuous variables than as discrete categories, because they are base on a ration between two continuous variables, summer evaporation and annual median rainfall. It would be feasible to agglomerate them into three major categories, as follows:

Wet - hyperhumid and perhumid
Moist – humid and subhumid
Dry – semiarid, arid and perarid.

The major categories (wet, moist, dry) would then become equivalent to biogeoclimatic zones and minor categories (hyperhumid, perhumid, perarid) would become equivalent to biogeoclimatic subzones. The price of this would be a certain loss of continuity and creation of an artificial discontinuity. The difference between perhumid and subhumid is no greater than that between subhumid and humid.

The ecosection in the Canadian scheme is roughly equivalent to major physiographic subdivisions of the Jarrah-Warren bioregions, such as the Southern Coastal Plain, the Darling Plateau, the Margaret River Plateau and the Blackwood Plateau. Because of the great disparity in size between the Darling Plateau and the rest, the former has been subdivided within the local classification scheme into southern, central and northern sectors. The central sector of the Darling Plateau consists of the catchment of the Blackwood River, which completely bisects the plateau within the project area, and is also a major physiographic feature in its own right. There are significant differences between the three sectors in topography, soils and vegetation.

The local vegetation complexes of Heddle *et al.* (1980) are similar to site series in the British Columbia classification, in that they describe a series of sites (toposequence) supporting a corresponding series of vegetation types, located on a given landform within a given biogeoclimatic subzone. They are not equivalent, as they are not supported by the same high level of synecological knowledge and hierarchical vegetation classification that appears to be available in British Columbia, so that abiotic factors play a greater role in their definition.

The resulting maps do not contain any equivalents of the British Columbia site types, which would not be mappable at the scale used for bioregion mapping (1:250,000 to 1;500,000). The nearest local equivalents to these are Havel's (1975a and b) site-vegetation types, mappable at the scale of 1:10,000 to 1: 50,000.

Pojar *et al.*'s (1987) make the point that in the upward progress in the hierarchy from site types to biogeoclimatic units there is a inevitable loss of information and flexibility, in that fewer and less specific interpretations can be made about biogeoclimatic units than can be made about site types. They consider the site types, which have the highest degree of homogeneity, the most appropriate level for deriving interpretations relevant to land management.

Banner *et al.*'s (1996) perception of the relationship between ecosystem classification and ecosystem mapping is highly relevant. Ecosystem classification is seen as providing the taxonomic framework for describing the nature and pattern of ecological units within a landscape, whereas ecosystem mapping is seen as the means of depicting the actual spatial distribution of the ecological units. Additional benefits of ecosystem mapping are also enumerated – the provision of ecological framework for land management, integration of abiotic and biotic ecosystem components on one map, provision of basic information for management interpretation, historic record for the monitoring of response of ecosystems to management and demonstration of ecosystem and landscape diversity. These are primarily seen as arising out of the multidisciplinary nature of ecosystem mapping.

The situation in British Columbia is also described by Mah *et al.* (1996, whose primary interest is in the use of the classification and maps in land management. They see the current methodology as being the product of merging and integrating several earlier attempts to classify and map forested lands. The maintenance of biological diversity is seen by them to be the primary issue in land management. Pojar *et al.*'s (1987) report a major increase in ecological awareness through the exposure of forestry staff to ecological classification and environment/vegetation relationships.

Other Canadian ecological studies, in particular the earlier forest ecology studies of Mueller-Dombois (1965) in southeastern Manitoba, shared with southwestern Australia the subdued topography, lower rainfall and gradual edaphic catenas in which water regimes play a key part. The key aspect of Mueller-Dombois studies is the development of the concept of ecological series, which he defines as group of two or more habitats along a transect, which differ from one another in different intensities of a major environmental control factor. An important concept developed by Mueller-Dombois and Ellenberg (1974) is that soil water regimes are, in the long term, imprinted in the soil profiles in such ways as the degree of leaching, the deposition of additional nutrients, the incorporation of humus and the development of gley horizons and fragipans, so that soil moisture regimes and nutrient regimes tend to be mutually correlated. This combination is then reflected in the vegetation patterns. Also relevant is Mueller-Dombois finding that under such conditions the understorey species reflect the water regimes qualitatively by their presence or absence, whereas the overstorey trees tend to respond more quantitatively, in terms of growth rates. Understorey species can thus be used as indicators of the site conditions. This parallels local observations and studies by Havel (1968, 1975a and b) and Mattiske (1979 to 2000).

In all Canadian work, considerable attention is given to chronology, that is the stages that vegetation of a given site passes through in the process of recovery from major perturbation such as wildfire. Pojar *et al.* (1987) go so far as to rank chronology (succession) level of importance to other levels of integration – local and regional. The explicit consequence of that is that a number of different communities may occur on the same time, dependent on site, disturbance, chance and time (Pojar *et al.*, 1987). Many of the classification schemes give not merely the climax vegetation found on sites free of major disturbances for a long time, but also the seral stages that might be found on that site during the various stages of recovery from a disturbance.

By comparison, seral stages are given relatively little attention in the classification schemes of the southwestern forests. The primary reason for this is that whereas Canadian forests mainly consist of fire-intolerant trees, which regenerate from seed after relatively infrequent fires, the southwestern forests consist mainly of fire-tolerant trees which mainly recover from frequent fire perturbations by vegetative recovery from epicormic buds and lignotubers. Havel (1975a and b) made an allowance for possible seral effects by not using understorey species of the jarrah forest that are known to regenerate rapidly in large numbers after fire from seed, as indicators. By contrast, Inions (1990a *and* b) was confident that young karri stands, regenerated by seeding after severe regeneration burns, did not have an intrinsically different understorey to old growth stands.

Ecological Land Classification

Rowe (1996), in considering the philosophical basis of ecological land classification, makes the point that classification and mapping are synergistic, although it is possible to carry out classification without mapping from sample plot data. He sees the chief benefit of combining classification and mapping in the fact that every part of the terrain has to be confronted and difficult in-between and odd-ball units cannot be avoided, as they can be if classification alone is carried out. He views the map boundaries as hypotheses expressing the map author's belief that important compositional and functional differences lie on either side of the boundary.

Rowe (1996) considers landforms and drainage patterns to be the most enduring of earth features, which are important for understanding and delineating ecosystems. He recognizes that the vegetative patterns which they generate may be modified and distorted by a variety of disturbances, such as fire, insect, wind and human activity, so that there is not an exact correspondence between forest stand boundaries and ecological boundaries. He also recognizes that, on a larger scale, the symmetry of climatic belts is broken and modified by configuration of continents and relief of the land. Landforms are the underlying key to patterning of climate, vegetation and soil, and the consideration of ecosystems without their abiotic components such as climate and soil, which control the reception and transformation of energy and moisture, is suboptimal.

Sims *et al.* (1996) view Ecological Land Classification as a combination of art and science which attempts to deal with the definition, recognition and representation of ecosystems across gradients of space and time. As such, it is the pre-requisite for the evaluation of difficult trade-off decisions regarding resource issues.

They therefore believe that such classification should be applicable to all land (and water) areas and suitable for a wide range of potential uses. It must be underpinned by testable and well-defined hypotheses, and recognise that the lines defining polygons on the map may at times be wide and fuzzy zones rather than sharp boundaries.

There is a considerable discussion in the Canadian ecological literature on the hierarchy of the ecological framework.

Pereira *et al.* (1996) argue that for an eco-regionalisation scheme to operate effectively, it must possess certain criteria, such as explicit explanation of spatial and temporal scales, a hierarchical construct of eco-regional domains, an explicit quantitative description of the eco-regional domain and the ability to be tested as a hypothesis. The ultimate objective of such a scheme is to simplify ecological complexity of the region under study. Toward that objective Pereira *et al.* (1996) advocate multi-level hierarchical nesting within which the higher categories (holons) spatially contain the lower level holons and functionally constrain them. In addition, the higher level holons (eg ecoregions) function and change at a slower temporal rate than the lower level holons (eg ecodistricts), and provide the context for the existence and function of the lower level holons. The lower level holons determine the rates of function of higher level holons. The hierarchy advocated is a nested, not factorial one, which means that the sub-levels of a given hierarchy may not directly correspond to one another. The approach advocated is a top-down approach, that is, the development of context precedes the prediction of a function, and the state of the whole must be known before the collective behaviour of the parts can be understood. Such an approach is claimed to provide a holistic insight, which would not be available with a bottom-up approach.

Bajzak and Roberts (1996) define an ecodistrict as a part of an ecoregion (mappable at 1;1,000,000 to 1;3,000,000) characterised by a distinctive pattern of relief, geology, geomorphology, vegetation, water and fauna, that is best mappable at 1:125,000 to 1:500,000.

An ecosection is a part of an ecodistrict throughout which there is a recurring pattern of terrain, soils, vegetation, waterbodies and fauna, that is best mappable at 1:250,000 to 1:50,000.

An ecosite is a part of an ecosection having a relatively uniform parent material, soil, hydrology and chronosequence of vegetation, that is best mappable at 1:50,000 to 1:10,000.

An ecoelement is apart of an ecosite displaying uniform soil, topographical, vegetative and hydrological characteristics.

In the case of Bajzak and Roberts (1996), the ecoelement is named after the dominant tree species (Taxus balsam fir) and is described by a structural profile, soil profile diagram and description and a diagram defining its position on the edaphic grid.

McNab (1996) claims that the derivation of models for classifying ecological types is a necessary prerequisite to mapping ecological units, whether in field or by geographic information systems. He also views the framework of ecological types as an aid to managing biological information and to understanding of ecological relationships over a range of scales. In his experience local types, which are generally equivalent to single vegetative communities, occur in predictable patterns in small areas of environmental uniformity on single landforms. They generally occupy tens to hundreds of hectares and are mappable at the scale of 1:24,000 to 1:60,000. At the next level of complexity, the landscape types encompass group of landforms in recurring areas of relatively uniform climate, geologic substrate soils and potential vegetation.

McNab used multivariate methods to identify landscape types, which were correlated with topographic and soil variables related to temperature and moisture gradients. Use of topographic and soil variables without knowledge of vegetative communities did not allow logical identification of ecological types.

Cartier *et al.* (1996), working in strongly disturbed region of Quebec, used a topographic and soil catena within which vegetation was recorded not as a single type, but as a set of separate stages between pioneer and climax stage. Like Mueller-Dombois (1965) in Manitoba, they found that the hydrological regimes along a topographical gradient were reflected in soil properties such as the depth of the solum, texture and organic matter incorporation. Unlike Mueller-Dombois (1965), they found that in their region of complex forest mosaics, diverse geomorphology and recurrent perturbations, ground vegetation was inadequate means of differentiation unless supported by the observation of site features such as soils texture and moisture regime.

Roberts *et al.* (1996), though working in a less disturbed region than that of Cartier *et al.* (1996), still found it desirable to to integrate vegetation and soil types to obtain forest type. They took the process one step further by integrating the forest type with landscape type (climate, parent material and relief) to develop a toposequence. In their description of vegetation, like Cartier *et al.* (1996), an allowance if made for the effect of disturbance, providing a description of vegetation pre and after fire. They considered the use of edaphic information essential to sound definition of the ecological position of the forest stands.

Matson and Power (1996) describe a methodology for developing and mapping a hierarchical Ecological Land Classification, developed for the New Brunswick province. The outstanding feature of the methodology is the emphasis on biologically significant criteria of the abiotic factors, in particular climate. As the classification is hierarchical, with climatically determined categories at the top of the hierarchy, the effectiveness of the classification depends on getting the climatic influences right. For this reason boundaries of the climatic regions were only accepted if the tree species or groups of species could be seen acting as ecological thermometers, that is, if the climate profiles explained the changes in forest composition between regions. At the second level of geomorphologic districts a potential fertility matrix was used to assess the biological significance of the chemical and physical properties of the bedrock. The continuum extended from felsic volcanics, which were considered to have low relative fertility (low capacity to supply basic elements such as Ca, Mg, Na) and low relative weatherability, to metasiltstones and mudstones which are richer in the basic elements and weather rapidly. Low weatherability was considered to be reflected higher elevational landforms. Howevr, subsequent validation indicated that igneous and metamorphic formations exhibited lesser range of fertility and lesser vegetative response than sedimentary formations. This was attributed to deformation, weathering and transport through glaciation, which reduced or obliterated association between parent material and soils, and hence between parent material and vegetation.

At the third level of classification, the units are Regolith Sections, defined as quaternary deposits that are homogeneous with respect to lithology, mode of deposition, depth, textural characteristics and coarse fragment content. The Regolith Sections are expected to support vegetative communities that are distinct from adjacent RCs due to their uniformity of parent material. Because of the nature of depositional processes, Regolith Sections with similar mode of deposition tended to be located in the same topographical environment.

At the fourth level of classification, that of the Site Level, the Regolith Sections were subdivided by elevation, aspect, slope, position on slope, soil drainage and soil moisture. Each site was predicted to support a distinct vegetational complex. They were named by the dominant late successional tree species. Grouped together the sites formed a landscape mosaic within each Regolith Section. The field sampling, which was done along transects oriented across topography, was used to generate a toposequence of communities, which was used as a visual check on the patterns of tree species.

The Climatic regions were found to differ in the number of tree species and in the composition of the overstorey. If postulated climatic regions were not found to differ in these criteria, they were merged. Each of the validated climatic regions was described in terms of its climatic and physiographic characteristics, in terms of the forest composition. The description of forest composition gave not only the presence of species and their pattern of distribution, but also absence of other species. Climatic patterns conducive to occurrence of fire, such as summer moisture deficit, and tolerance of the various tree species to fire, were a significant consideration. In regions subject to strong impact of agriculture the biotic proved less useful. The boundaries of the regions were defined by a combination contours and occurrence of climate-dependant tree species, eg relief greater than 120 m and decrease in abundance of tolerant hardwoods.

As part of the validation process, the strength of species-site relationships was examined by comparing the number of plots on which the relationship held true, as compared to the total number of plots on which the species occurred. The strength of the species/site relationship was taken as the measure of the success of the upper hierarchy of the classification to isolate factors that control the distribution of forest ecosystems.

Matson and Power (1996) consider the Ecological Land Classification to be more than just ecosystem identification and mapping process. They see as one of its achievements the improvement in the understanding of the ecosystems' form and function by linking the abiotic and biotic components of each system. The distribution of tree species was considered to be pivotal to understanding and validating the influence of abiotic factors on forest systems, based on the prediction that plants are the ultimate integrators of environmental influences and are thus representative of the environment in which they grow.

They also concluded that the development of an accurate Ecological Land Classification product was achieved through trying to reject rather than trying to support the predicted ecological relationships.

Smith and Carpenter (1996) compare the two possible approaches to ecological classification and mapping at the sub-region level. The bottom-up approach is to define and map lower level ecological units, identify ecological patterns and then elucidate the ecological processes they infer for the next higher level. This process allows repetition of the process until they reflect the ecological conditions at the scale of interest. The second, top-down approach, is to use higher level units to filter information on patterns and processes before applying the multifactor criteria at a finer level of resolution. The common approach is to analyse individual components and then , using a series of overlays , combine them into one map. It is a mechanical process the product of which needs to be subsequently validated.

Smith and Carpenter (1996) consider that the challenge in classification is to distinguish natural associations of ecological factors, the relationships between them and their appropriate spatial and temporal framework. The additional challenge in developing ecological classification that is hierarchical and integrative arises out of the fact that most published maps and data sources are developed at a single scale, areoriented toward individual disciplines and are often biased due to multitude of political and administrative boundaries.

They make the observation that bedrock geology is most useful where the subsequent geological processes (eg glaciation in northeastern USA) are predominantly erosional. Under these conditions the highest elevations and the most rugged topography is associated with resistant granitic or silicate rock.

Smith and Carpenter (1996) consider the development of ecological units to be a highly iterative process, during which new information and understanding must be incorporated into the map units and interpretations as they become available. Part of the process is the use of new data sets to overcome geopolitical bias, to test the integrity of ecological units and to measure the precision of ecological unit boundaries and to integrate many disparate sources of information.

Development of Environmental Framework

Climate

There have been many attempts at defining those key features of the climate of southwestern Australia which determine the vegetation patterns. There is reference to climate in every mapping and classification scheme, as well as several stand-alone discussions of the climate-vegetation interaction.

Churchill (1961) described a strong north-south and east-west patterns in the distribution of individual species, ranging from those confined to the humid south, such as *Eucalyptus diversicolor, Allocasuarina decussata, Chorilaena quercifolia* and *Agonis juniperina*, to those only entering the forested region along its northern and eastern margin, such as *Eucalyptus astringens* and *Eucalyptus accedens*. He also illustrated a wide differences in the climatic range of the species, such as the narrow range of the species described above compared with the very broad range others, such as *Nuytsia floribunda, Banksia attenuata, Macrozamia riedlei* and *Melaleuca preissiana*, which occur throughout the forested region and beyond whenever suitable edaphic conditions are present.

Havel (1975b) studied the effect of climate on vegetation by field surveys of a set of sub-catchments spanning the full climatic range of the northern jarrah forest, from 600 to 1300 mm of annual rainfall, and found climate to be a strong determinant of broad changes in structure and composition of vegetation, particularly on the valley slopes. In addition to the main east-west gradient in vegetation, which parallels a strong rainfall gradient, he also found a northeast-southwest gradient which was more difficult to explain in terms of the climatic criteria then available. He also observed that the line of high monadnocks that rises above the plateau and has a northwesterly orientation appears to be exercising an influence on tree distribution patterns, in that the trees with southwestern centre of distribution do not occur east of it.

Beard (1981) analysed the climatic patterns for the region as a whole in relation to vegetation. He described the dominant role of high-pressure anticyclones in generating dry summer conditions and the dominant role of low pressure cyclones in generating a relatively high and reliable rainfall in winter. He also pointed out that there are two rainfall gradients in the region, related to the south and west coast respectively. Of these, the former is a sharper and stronger as it is associated with the principal rain-bearing winds, the westerlies. It is accentuated by the uplift caused by the Darling Scarp, so that high rainfall is experienced about 10 km east of the Scarp as far north as Jarrahdale, just southeast of Perth. This rainfall is strongly concentrated in the winter season. By contrast the gradient associated with the south coast is due to onshore southerly winds, and in magnitude is much less. It is, however, also much less seasonal. In the south of the forest region the two gradients overlap and give rise to a much longer rainy season, and consequently lesser and shorter drought. This is reflected in the number of months without rain, in that Perth and Albany, occurring at the northwest and the southeast of the forested region respectively, have comparable annual rainfall of 800-900 mm, but whereas Albany has only one month with lowest monthly rainfall of 0 mm, Perth has six such months.

Beard (1981) also refers to the differences between the coastal localities (no frosts at Perth and Albany) and inland localities, where winter night frosts are relatively common. The difference in temperature regimes of coastal and inland localities was also observed by Churchward *et al.* (1989), who noted that in the southern half of the region there was a downward gradient in temperatures from coast inland in the winter, and upward gradient in summer. This adds up to a much greater temperature range inland than on the coast. Similar temperature gradient was also observed for the karri region by Inions (1990).

Beard's main preoccupation is with climatic indices. He considered that under local conditions that both Koeppen's (1936) and Thornthwaite's (1931) classifications do not reflect the vegetational patterns well, and prefered the Bagnouls and Baussen's (1957) ombrothermic diagram based on the formula r = 2t, by which any month not meeting this criterion is considered to be dry. In his adaptation of the system to the southwest region he recognizes four climatic types based on the number of dry months:

> moderate mediterranean of 3-4 dry months, covering the southern half of the forest region,
>
> dry mediterranean of 5-6 dry months, covering the northern half of the forest region,
>
> extra dry mediterranean of 7-8 dry months, which just touches the forest region in the dry northeast, and
>
> semi-desert mediterranean of 9-11 dry months, which occurs completely outside the forest region.

Beard (1981) has sought a further refinement by dividing the zones defined by Bagnouls and Baussen's (1957) formula into eastern and western sectors. The entire forest region considered here falls into the western sector.

Beard (1981) also examined the effective rainfall formula of Prescott (1952), in which effective rain per month is defined as

r = 0.54 x e 0.7.

This formula defines the karri region as having over eight month of effective rainfall, as compared with less than 6 months for the northeastern wandoo woodlands. The chief limitation of the formula appears to be that a considerable proportion of the southern coast between Albany and Raventhorpe, down to an average annual rainfall of 500 mm, much of which does not support forest, comes up as climatically superior to tall open forest north of Manjimup. There appears to be an over compensation for the cooler climate and longer rainy season along the south coast. Much the same appears to be also true of the Bagnouls and Baussen's (1957) formula.

Beard (1981) gave considerable consideration to past climates, chiefly drawing on the studies of Churchill (1961, 1968). These studies indicated series of climates alternatively drier and wetter than the present climate. The current climatic patterns are considered to have persisted over the past 5000 years. The occurrence of outliers of the tree species outside their current range is attributed to these climatic changes.

The most detailed analysis of climate associated with vegetation study is that of Inions (1980), who analysed seventeen climatic measures (variants of temperature, precipitation, radiation, evaporation and raindays, generally for the year as a whole and for the wettest and driest quarters) from the karri region by polythetic agglomerative clustering techniques and by principal component analysis. He derived three major and eight minor homoclimes. The three main homoclimes represented high rainfall western portion, warm medium to low rainfall inland portion and cool, high rainfall south-coastal portion of the species distribution respectively. Subdivision of these to the eight minor homoclimes improved the definition. Unfortunately comparable studies are not available for the bulk of the forested region.

Gentilli's (1988) analysis of the climate of the jarrah forest appears to be the most relevant. Its coverage is virtually identical to the area mapped by us, in that it does not just cover the main jarrah block but includes the karri forest and western wandoo woodlands as well. It analyses the climatic components in great depth and puts forward a diagram relating annual rainfall and summer evaporation to the occurrence of the main forest types, which matches our field observations better than any of the schemes discussed above. It also relates the climate of the southwest to worldwide climatic classifications.

Gentilli (1988) supplemented the inadequate distribution of weather stations within the forest region by calculations, and found that rainfall could be best interpolated by regression on the basis of latitude, distance from the sea and altitude. He sees the 635 median isohyet as the eastern margin of the jarrah forest and the 900-1200mm belt as its optimum. However, the rainfall exceeds the optimum in a relatively narrow zone 10-12 km east of the Darling Scarp, which causes a three hundred metre uplift of the westerly airmasses. It also exceeds 1200 mm in the proximity to the southern coast.

The characteristics of the climate of the southwestern region are that it is a warm temperate (coldest month below 18 C) and summer dry (driest summer months receiving less than 1/3 as much rain as the wettest winter month). This puts it into Koeppen's (1936) category Cs, usually described as mediterranean. Kopppen subdivided this into categories a and b according to whether the average temperature of the hottest month is above or below 22 C. Locally that divides the southwestern region along the line from Bunbury to Kattaning.

Gentilli (1988) considers Koeppen's classification inadequate, in that the Cs category goes northwards beyond the occurrence of the jarrah forest. He attributes that to the failure to give adequate consideration to the duration of the rainy season, which within the southwest forest region varies from 5 in the northeast to 9 in the south. For that reason Creutzburg's (1950) and Bagnoulls and Gaussen's (1957) classifications, which take this into consideration, give a better match.

However, even these classifications are suboptimal for the southwestern region, with its considerable latitudinal spread and strong winds and high temperatures. For that region Thornthwaite's (1931) classification which incorporates the concept of precipitation effectiveness (PE) which utilises monthly rainfall (r) and monthly temperature (t).

In Thornthwaite's classification forest is considered to need annual Precipitation Effectiveness between 64 and 128. Gentilli (1972) refined Thornthwaite's classification by the introduction of climatic subdivisions, whereby the jarrah forest (B – humid) is distinguished from jarrah woodland (C – subhumid).

Gentilli (1988) brought in a further refinement by introducing the concept of summer stress, to take into account the particularly strong summer drought lasting 4-7 months, which is characteristic of southwestern Australia. He found that the duration of the drought was influenced by latitude, in that northern localities tended to have a more severe drought. There was also an influence of topography, that is, whether a locality is exposed to rain-bearing winds or cut of from them by higher ground. He also found that the lack of rain in one month can be mollified by rain in preceding or following months. A further significant factor was solar radiation, and its interception by cloudiness, the latter factor being stronger in the south.

Gentilli also described a gradient in temperature, the average daily maxima for February ranging from 33 C in the north at Upper Swan to 27.6 C at Manjimup in the south. Neither Gentilli (1988) nor Churchill (1968) considered temperature to be a very significant direct factor in forest distribution, though a colder area prone to night frosts was identified near Wandering and Williams, with temperatures dropping as low as – 4.5 C.

According to Gentilli (1988) not only the magnitude of the rain, but also its timing is important. The heaviest rain events tend to contribute relatively more to run-off than to soil storage and vegetation than less intensive ones. Similarly there is a difference between late winter rains, which fall on saturated soil, and autumn rains, which fall on unsaturated soil.

Gentilli (1988) considered that climatic classification for forests should take account for both the favourable factor (rainfall) and the severely limiting factor (summer stress). He analysed water balance between rainfall and evaporation at the beginning and end of the rainy seasons and used it to divide the forest region into a number of categories, ranging from perarid at the northeastern margin of the forest at York to hyperhumid in the south at Pemberton and Denmark.

His most effective definition of climate suitable for forest growth was the plotting of median annual rainfall against total summer evaporation (December to February) and fitting the various localities in the southwest within that framework. The main karri forest occurrence was delimited by summer evaporation of less than 500 mm and annual median rainfall of more than 1000 mm, though relicts of karri occurred at lower rainfall down to 700 mm. The dominance of jarrah was best expressed between the above criteria and summer evaporation less than 750 mm and annual rainfall of more than 800 mm. In more stressful climatic environment of summer evaporation exceeding 750 mm and median rainfall dropping below 800 mm the forest reduces to woodland. Below median rainfall of 600 mm jarrah occurs only as small outliers. In defining the vegetation types within the climatic framework, Gentilli used a combination of curves and near-straight lines.

Gentilli (1988) has also related climate to fire behaviour, which is a very powerful ecological factor in the region, in that apart from offshore islands no part of the southwestern region is exempt from periodic fire occurrence. Gentilli examined the occurrence of thunderdays, which are the chief natural cause of ignition. He related the occurrence of thunderdays to the formation of a line of instability, associated with a barometric trough offshore, and considered the danger to be greatest when the land inland from the trough was hot and fuels dry. The rise of the fast, moisture-laden westerly airstreams over the Darling Scarp contributes to the instability, and the sudden changes in wind direction associated with the passage of the barometric trough accentuate the danger. Yet another factor contributing to the severity of fires in the region are the anticyclones which dominate the summer weather pattern. Associated with them are the strong easterly winds, which in summer are both hot and dry as they enter the forest region from the dry inland. The worst conditions arise when a series of days with hot and dry northeasterly winds is followed by a trough, so that risk of ignition is high and the high temperatures and dry fuels are conducive to extreme fires.

With the accent on the dry and hot summers as determinants of the vegetation dynamics, there has been insufficient attention to the reverse side of the coin, namely that in winter the relatively high and reliable rainfall is not balanced by the evaporation and transpiration demand. This therefore means that in winter the vegetation also has to cope with water surplus in the root zone, unless the topographic position and the soil texture and structure are conducive to rapid drainage. The potential for waterlogging exists throughout the project area, but in the northern half it is reduced by the strong east-west topographic gradient generated by the Darling Scarp. The belt close to the Darling Scarp is generally well-drained as streams are deeply incised. It is only further inland, in the headwaters of streams, where valleys are shallowly incised, with broad flat floors and mild gradients, that waterlogging becomes more prevalent. However, it is in the southern half that the scope for waterlogging is maximised. Here the Darling Scarp is less prominent and the Raventhorpe Ramp consists of belts of weakly sloping shelves separated by belts of hills composed of igneous rock. The shelves are generally poorly drained. The maximum scope for waterlogging is along the south coast, where high dune systems deflect the streams toward a few estuaries, so that much of the coastal plain behind the dunes is poorly drained.

The importance of water-logging regimes in determining the resultant vegetation was also recognized by Havel (1968) in his studies on the Swan Coastal Plain. The latter relationship between soil moisture and patterns in vegetation on this latter project has been extended and further clarified by Heddle (1980) and more recently by Koch and Mattiske (E.M. Mattiske and Associates and Mattiske Conmsulting Pty Ltd 1976 to 2000) through triennial reporting requirements on the Swan Coastal Plain to the Water Authority and the Water nad Rivers Comimssion of Western Australia.

Geology

The dominant geological feature of the forested region of southwestern Australia is the Darling Scarp, one of the major tectonic features of the earth, which extends from the north of the region to its southern limit near the Southern Ocean (Biggs and Wilde 1980). It is the surface expression of the Darling Fault, which is a massive normal fault, which separates the crystalline rocks of the Yilgarn Block to the east from the sedimentary rocks of the Perth Basin to the west.

The Yilgarn Block forms a stable shield composed linear belts of Archean metamorphic rocks (sedimentary and volcanic) with large granitic intrusions. The Archean rocks, which have a northwesterly lithological and structural trend, determine the major grain of the country. There are some minor areas metamorphosed sediments assigned to Proterozoic along its western margin and some Phanerozoic sediments in depressions within the shield. The shield extends eastwards beyond the inland boundary of the forested region.

The Archean rocks include granitic rocks (granite, quartz monzonite, granodiorite and adamellite) in the form of large batholith; gneisses, migmatites, metasediments, acid and basic volcanics, quartzite, schist in the form of metamorphic belts and dolerite dykes in form of sheetlike intrusions (Biggs *and* Wilde,1980). The metamorphic rocks occur in several belts, such as Jimperding in the northeast, Chittering in the northwest and Saddleback in the mid-north, and Balingup between Harvey and Bridgetown in the centre of the region.

The Permian sediments in the depressions within the Archean shield consist of conglomerate, sandstone, siltstone, shale and seams of sub-bituminous coal. They are entirely overlain by Tertiary sediments. Extensive fluviolacustrine deposits assigned to Eocene overlie the Archean shield near Boyup Brook and more resticted area of sediments occur near the Darling Scarp, such as sandstone at Donnybrook and conglomerate at Kirup.

The Perth basin is a deep trough filled with Phanerozoic sediments up to 15 km deep. The Permian and Createaceous rocks within it comprise mainly sandstones, but interbedded with them are siltstones, shales, clay and chalk, mainly of marine origin. They only outcrop in the northwest of the region, on the dissected portions of the Dandaragan Plateau, and in the southwest, on the dissected portions of the Blackwood Plateau. These two plateaux are capped by sand and laterite and are separated from the Swan Coastal Plain by scarp-like features of marine origin, referred to as Gingin and Whicher Scarp respectively. The Blackwood Plateau merges at its southern margin into the Scott Coastal Plain, also known as the South Coast Plain, which is low-lying and swampy. On the coastal plains the Cretaceous deposits are covered by Cainozoic deposits of conglomerate, sandstone, clay and sand. The sands have varying proportion of calcium, often in form of shell segments, ranging from very high near the coastline to very low away from the coastline. The proportion of calcium is interpreted as a reflection of the degree of leaching. Those that have a very high proportion calcium and are consolidated are referred to as calcerenite or Tamala limestone. There are also lake, swamp and estuary deposits within the plains, composed of clay, sand, peat, gypsum and diatomaceous earths.

Within the Blackwood Plateau there are outcrops of Bunbury Basalt within the dissection of the Blackwood River and its tributaries. The basalt also outcrops on the coast of Indian Ocean at Bunbury, and on the coast of the Southern Ocean at Point D'Entrecasteaux. It is considered to be a basalt flow that infilled pre-existing valleys, and is limited in extent.

In the southwest of the region the Blackwood Plateaux abuts on to the Leeuwin-Naturalist Ridge, a block of Proterozoic gneissic and granitic rocks in the form of a relatively narrow, undulating plateau, described in some publications as the Margaret River Plateau. At its western edge, near the shore of the Indian Ocean, it is overlain by a strip of Tamala limestone, which in turn is partially overlaid by unconsolidated dunes.

South of Manjimup the Yilgarn Plateau abuts on to the Albany-Fraser province, also described as the Albany-Fraser Orogen, which is a belt of metamorphic rocks such as migmatite and gneiss, intruded by granitic batholiths. This belt, which has a west-northwest orientation, slopes southwards toward the Southern Ocean and is also referred to as the Raventhorpe Ramp. The batholiths outcrop as large domes. The low-lying portions of this belt are infilled with Eocene deposits and form swampy plains. The plains drop from 160m a.s.l. in the north almost to sea level near the south coast. The batholiths mostly rise more that 100 m above the intervening plains, but some, like Mt Lindesay, are much taller. In the southeast of the forested region the ramp is covered by marine deposits described as Pallinup Siltstone, which slope from 180 m a.s.l. inland to 40 m near the coast. There are outcrops of the granitic and gneissic rocks within the South Coast Plain, but the bulk of the coast consists of Tamala limestone and of unconsolidated sands in the form of parabolic dunes. Behind the dunes are low-lying unconsolidated coastal plain deposits of the type already described above for the Swan Coastal Plain, but the proportion of peaty deposits is higher here than on the Swan Coastal Plain.

There are also deposits on the higher part of the landscape, mostly in the form of grey sands with pebbles and grits, whose origin is under discussion (Churchward *et al.*, 1988).

The land surface of most of the region has been subject to a complex process of weathering, denudation and redeposition. Of particular importance is the formation of deeply weathered mantle over both crystalline and sedimentary country rocks, which tends to have an upper horizon of sesquioxides in form of nodules and crusts, and is underlain by mottled and pallid zones of kaolinised country rock, and ultimately, sometimes as deep as 50 meters, by unweathered rock. Such profile is described as laterite (Stephens, 1946), and is particularly common on upland surfaces. Within valleys and on scarps it has been removed, to varying degree, by the process of erosion. This process, which is still on-going, is the key determinant of landforms and soil patterns.

Geomorphology

Geomorphic mapping can be an important aid to vegetation mapping, particularly in regions where floristic differences are not reflected in the structure of the vegetation and are thus not mappable from aerial photographs. This is the case in the jarrah forest, where one species is dominant over hundreds of thousands of hectares with only minor structural variation.

The importance of geomorphology in determining the soil patterns, and hence vegetation patterns, has been recognised in Western Australia for some time. The earliest of this work dates to the 1920's and 1930's (Clarke 1926, Jutson 1934). The early work was on a continental scale, and thus serves a framework for this study, rather than an aid to mapping. The whole of this project falls within Jutson's (1934) Southwest (Swanland) physiographic division, which extends beyond the project area both to the north and the east. It falls just into two of Clarke's (1926) natural regions, Perth and Jarrah.

More detailed geomorphologic mapping, on a scale relevant to this project, began in the agricultural areas (Mulcahy *et al.* 1961). It was then introduced into the forested areas by Mulcahy *et al.* (1972), first into the Helena catchment in the northeast of the project area. It was at this stage that the linkages between geomorphology and plant ecology begun to be developed through mapping of vegetation over a range of geomorphic units by Havel (1975 b). A linkage between geomorphology and land use was established for the Wungong catchment through the cooperation of a geomorphologist and a forester (Churchward and Batini (1975). On occasions the forest ecologists drew attention to landforms which, on basis of vegetation studies, warranted new landform category, such as the Cooke landform (Havel 1975b). The geomorphologic mapping was then extended southward by McArthur *et al.* (1977) to the Murray catchment, again as a basis for a joint land use planning project. A separate study of geomorphology was carried out by Finkl (1976) in the Blackwood catchment in the centre of the current project area. Bettenay *et al.* (1980) surveyed the geomorphology, hydrology and plant ecology of a series of subcatchments of the Collie River.

All the above studies were combined by Churchward and McArthur (1980) to cover the entire forested region north of the Blackwood River (System 6 Region), and the set of three maps developed by them was utilised by Heddle *et al.* (1980) to map the vegetation at a scale of 1:50,000 of the region for the purpose of delineating national parks and nature reserves.

Churchward and McArthur (1980) considered the slope of the land and the nature of the soils as determinants, on one hand, of the landform-soils units that they were mapping, and on the other hand, of the way that the land could be used. They used five of the geomorphological provinces, namely:

> the Darling Plateau of Precambrian crystalline rocks
> the Swan Coastal plain of Aeolian and fluviatile sediments
> the Dandaragan Plateau of Mesozoic sediments
> the Blackwood Plateau of Mesozoic sediments
> and the Collie basin of Permian and younger sediments

as the major subdivisions of System 6 region that they were mapping.

They recognised that with the exception of the Swan Coastal Plain, these provinces were covered by a mantle of weathered rock, often as deep as 50m, the upper horizons of which are frequently ferruginous and bauxitic and are referred to as the lateritic profile. They observed that the mantle was subject to erosional modification which exposed the weathered and unweathered materials and that the product of the erosion were distributed downslope. This gave a rise to a predictable soil patterns, determined by the degree of removal of the weathered mantle. Generally the upland interfluves are still mantled by the laterite. The valley slopes carry catenas of soils determined by their steepness and by the geological nature of the substrate.

Churchward and McArthur's (1980) subdivision of the largest of these provinces, the Darling Plateau, thus is:

Lateritic Uplands
Minor Valleys
Major Valleys including Slopes and Floors
Major Valley Floors and
Major Valley Slopes and Scarps.

These subdivisions were not actually mapped, nor given any generic name.

The lateritic uplands were subdivided into six mapping units. Churchward and McArthur's (1980) considered their mapping units, based on aerial photographs and contour base maps of between 1:25 000 and 1:50 000, to be approximately equivalent to soil associations. The units were given names of the locality in which the particular landform was best expressed.

Dwellingup	extensive uplands with coarse gravels in the west and northwest
Yalanbee	extensive uplands with fine gravels in the east and northeast
Hester	residual narrow crests in the south

Similarly the valleys were subdivided according to the degree of dissection. The detailed subdivision of the geomorphological provinces of Churchward and McArthur (1980) is given in Appendix C.

In the southern half of the project area, a broadscale linkage between soils and vegetation was first described by McArthur and Clifton (1975) for the Pemberton district as an aid to land use planning. Basically they first reviewed past soil studies in light of new the nomenclature of Northcote *et al.* (1967), and then defined the dominant soil types within the region. They mapped several subdistricts arranged in a continuum from the uplands of the Darling Plateau in the north, through the dissection of the plateau toward the southwest, the zone of isolated granitic hills and broad sandplains further south and finally the southern coast, with its succession of sand dunes. In each survey area they described an association of soils and the component soil types. They also looked at the relationship between these soil types and the vegetation that they carried.

Some of the concepts developed by them were a starting point for subsequent more detailed studies. Their work was subsequently expanded by Churchward *et al.* (1988) to cover the bulk of the south coast and its hinterland from Northcliffe to Mt Manypeaks. The descriptions of vegetation associated with the various landforms provided in this latter work facilitated the establishment of linkages between the geomorphology, landscape and vegetation.

Churchward *et al.* (1988) covered the full range of geomorphic variation from the Darling Plateau to the coast of the Southern Ocean, from the stable lateritic uplands in the north through several belts of crystalline uplands and intervening sandy plains referred to as the Ravensthorpe Ramp, which progressively drops in altitude, to the Southern Coastal Plain and ultimately to the sand dunes and the outcrops of crystalline rock of the south coast.

The three major categories described by them were

I. Units developed on granitic rocks and associated unconsolidated sediments
II. Units developed on siltstones and sandstones
III. Units developed in coastal Aeolian and fluviatile sediments

This subdivision does not distinguish between the Darling Plateau (sensu stricto) and the Ravensthorpe Ramp, though several north/south profiles illustrating the step-wise fall towards the south coast are given. This is presumably because there is no clearly defined boundary between the Plateau and the Ramp and because the same assemblage of crystalline and sedimentary parent material is found on both, though the proportions at the southern and northern extremes are markedly different. In the physiographic map of the study area distinction was made between the undulating plateau on deeply weathered rocks to the north (Darling Plateau sensu stricto), the complex of hill belts and sandy swampy corridors to the south (Ravensthorpe Ramp) and dissected plateau of deeply weathered rocks in the west, which is the region primarily described by Churchward (1992).

Parallel to the work of the CSIRO Division of Land Resources by Mulcahy, McArthur and Churchward, the Department of Agriculture commenced the Land Resources Series which filled in some of the gaps in geomorphologic mapping. Initially the latter mapping did not include areas of State Forest. The areas mapped in the north were the Mandurah and Murray region (Wells 1989), the Darling Range east of Perth (King and Wells 1990) and the Northam Region (Lantzke and Fulton 1992). In the southern region, Tille and Lantzke (1990) surveyed the Busselton - Margaret River - Augusta region. The last study of Churchward (1992) in the Manjimup region also formed part of this series, though retaining the CSIRO approach. The key central region of Wellington-Blackwood, which approximates the southern third of the area mapped by Churchward and McArthur (1980) as part of the System 6 project, has been recently remapped from the point of view of land resources (Tille 1996). Concurrently with the vegetation mapping, land resources mapping was in progress on the Blackwood Plateau covered by Tille and Lantzke (1990) in the west and Churchward *et al.* (1998) in the east. Smolinski (1999) was concurrently mapping the largest as yet unmapped area south of the Blackwood, east of Manjimup and north of the south coast and hinterland. The maps have been made available, but full description of the mapping units is yet to be published.

There are differences in the approaches taken by CSIRO and Department of Agriculture. These are reflected in the detail of mapping, and hence in the precision of vegetation mapping. However, both approaches have provided valuable linkages between geomorphology and vegetation, which have facilitated the mapping of vegetation in the South-West Forest Region in Western Australia.

There has been a progressive development of concepts and terminology in the land resources surveys of the Agriculture Department, which has culminated in the Wellington-Blackwood survey (Tille 1996). In this publication, the hierarchy of soil-landscape mapping units has been formalised. The current structure of the hierarchy is:

Regions

These are broad subdivisions of the Australian continent. The project area is a subset of the Western Region.

Provinces

These are determined on broad patterns of soils and landscapes and provide a broad overview of the whole state at the scale of 1:5,000,000. The project area is a western subset of the Avon province.

Zones

These are defined on geomorphological and geological criteria and are suitable for getting regional perspectives at the scale of 1:1,000,000. The project area comprises the following zones of the Avon province:

Leeuwin
Donnybrook Sunkland
Warren-Denmark Southland
Western Darling Range
Eastern Darling Range

Systems

These are areas with recurring pattern of landforms, soils and vegetation suitable for regional mapping at scale of 1:250,000. They are considered to correspond to the land systems of Christian and Stewart (1953).

Subsystems

These are areas of characteristic landform features containing a defined suite of soils, and are suitable for producing maps of catchments at the scale of 1:50,000 or 1: 100,000.

Phases

These highlight particular features, such as rock outcrops and poorly drained flats.

The hierarchical system described above has as yet not been applied to the whole of the project area.

The full description of the various maps, in particular of the component landforms, is given in Appendix C.

Flora

It is not proposed to cover all vascular plant species in this section, but merely to highlight some key features of the south western flora. During the ecological studies associated with the vegetation mapping of the south west forest region, Mattiske and her team identified some 108 families, 436 genera, 1856 within the project area, Appendix A. This is comparable with the figure quoted in the recent estimate for the Regional Forest Agreement (RFA 1998a) of some 3244 native vascular plant taxa in the area, which includes reference to all historical flora collections in the CALM State Herbarium data base.

As pointed out by Hopper (1979), this number is likely to continue to increase as taxonomic research progresses and more detailed studies are undertaken in the areas which have been sampled less consistently.

Other estimates of flora richness are 1628 native taxa for the southern portion of the Regional Forest Agreement area, the Warren bioregion (Hopper *et al.* 1992) and 784 native taxa for the northern position, the Jarrah bioregion (Bell and Heddle 1989).

The second important feature of the flora is the high degree of endemism. Hopper (1979) assessed it at 68%, but anticipated that the proportion would be increased to 75-80% through revision of south western genera.

The largest families are considered to be Papilionaceae, Orchidaceae, Myrtaceae, Proteaceae (Hopper *et al.* 1992; Bell and Heddle 1989). The tree species are primarily derived from the Myrtaceae family, in particular the genera - *Eucalyptus, Corymbia, Melaleuca* and *Agonis,* and to a lesser degree from the Proteaceae (*Banksia, Xylomelum, Persoonia*), Mimosaceae (*Acacia*) and Casuarinaceae (*Allocasuarina, Casuarina*) families.

Many of the genera are highly poly specific (*Eucalyptus, Acacia, Melaleuca, Banksia, Allocasuarina*), with individual species often occupying different positions in the ecological spectrum.

The more unusual components of the flora are arborescent root parasites (*Nuytsia floribunda, Exocarpus* spp., *Santalum* spp.) and arborescent monocotyledons (*Xanthorrhoea* sp., *Kingia australis, Dasypogon hookeri*).

The nomenclature followed in the vegetation mapping project is that defined by the Department of Conservation and Land Management through their MAX and Flora Base listings which are available to Mattiske Consulting Pty Ltd under a licensing agreement.

System 6 – Northern Section of the Darling Ranges

An essential early step in the development of a mapping system based on a number of geographically disjunct or partially overlapping classifications is to establish whether there is sufficient continuity. If the classifications had employed uniform data collection methodology, the logical approach would be to reanalyse the data quantitatively and arrive at a new, overall scheme of classification. Unfortunately, the data collection has taken place over a period of over 40 years, using divergent plot sizes and recording criteria (presence/absence, percentage cover, frequency). Considerable changes have taken place over this period, such as redefinition and renaming of taxa, description of subspecies and varieties, identification of new taxa and declaration of certain taxa as invalid. Most of these can be allowed for if the collection on which the classification is based still exists (which is not always the case), but some cannot. The change in the name of one of the key tree species of the region, marri, from *Eucalyptus calophylla* to *Corymbia calophylla*, is easy to allow for. The subdivision of the most prominent species of the region, jarrah (*Eucalyptus marginata*) into three subspecies whose geographical ranges partially overlap, is impossible to trace backwards in time. There is no logical means whereby it could be decided which of the three subspecies was being observed by someone twenty years ago in a district where the subspecies overlap. It is highly likely that the classifications and ordinations of Havel (1975a) and Loneragan (1978) of the northern jarrah forests/woodlands may have been much more informative and clear cut if the definition of the subspecies had been completed by then.

Because there are so many qualifications about virtually all of the past classifications, comparisons between them had to be done subjectively, allowing for the taxonomic changes that have taken place.

The concepts of Pojar *et al.* (1987) were utilised in bringing together the various classifications, but in terms of methodology a less stringent version of the Braun-Blanquet system, namely that of Bridgewater (1981), was used. There is, however, a difference between this study and that of Bridgewater, in that he begins with raw data in the form of relevés, whereas this study begins with classifications in which plots have been already aggregated into site groups (community groups or types) and the representative capability of the species has already been tested. For instance, Havel (1975a) and Strelein (1988) subjected their indicator species to the scrutiny of how tightly and reliably they defined a particular vegetation type, and rated the species accordingly. Similarly, a species was only listed in Wardell-Johnson *et al.*'s (1995) matrix of species x subtypes if its constancy for that subtype exceeded 50%.

The integration of the various classifications in the project area proceeded outwards from the region already covered by earlier mapping, namely the northern jarrah region (Heddle *et al.*, 1980), for which an ordination/classification system, related to landform by field mapping and quantitative analysis, already existed (Havel 1975a,b). As a result, there already was a known array of species groups associated with particular sets of environmental conditions that could serve as links to other classifications. The details of these associations are given in Appendix F.

In linking the various classifications, a distinction has been made between those that are an intermediate link in a chain and those that are terminal. In the case of the former, the individual species and the site groups have been used to form a species / site matrix. This matrix was then manipulated to get the most effective constellations of species. These constellations are considered as indicator species groups or just species groups. The comparison of classifications was based on species groups, that is species which tend to occur together under similar environmental conditions across classifications, as for instance the SAMORG (species occurring on moist sands with high incorporation of organic matter) group of *Adenanthos obovatus* and *Dasypogon bromeliifolius* which recurs in numerous classifications.

The species groups, especially those indicative of average conditions (neither excessively dry or wet, of intermediate fertility and soil texture) do not remain constant from one classification to another. For instance, the GRAMED (lateritic gravels in medium rainfall) species group contains *Banksia grandis, Hovea chorizemifolia, Persoonia longifolia* and *Adenanthos barbiger*) in Havel's (1975a) classification. In Strelein's (1988) study, *Adenanthos barbiger* becomes too rare, and *Persoonia longifolia* becomes too common, but the core species of *Banksia grandis* and *Hovea chorizemifolia* remain. They are joined by new species (*Gompholobium ovatum, Agonis hypericifolia*) with similar distribution patterns.

The alternative approach is to link the species by referal to site groups (vegetation types or community groups) directly. It is less obvious, but more economical in terms of effort, as the intermediate step of establishing species groups can be avoided.

It is an approach, which is particularly suitable for terminal classifications, that is those that are an end point in a chain of classifications, such as Gibson's (personal communication) classification of coastal vegetation, or Worsley Alumina's (1999) classification and maps of eastern jarrah and wandoo woodlands.

For instance, in the latter classification, *Adenanthos barbigera, Banksia grandis, Hovea chorizemifolia* and *Persoonia longifolia* all occur on site groups S, ST, SP, P and H, but are absent from site groups M, Y, L, D and AY. By contrast *Trymalium floribundum, Hypocalymma angustifolium, Baeckea camphorosmae* and *Eucalyptus wandoo* occur primarily on site groups Y and L, with extension on to AY and D, but are absent from S, ST, SP, P and H.

The approach is also suitable for classifications that are intermediate links to other classifications, such as that of Havel (1975a). The species group shown above to be linked to site groups S, ST, SP, O and H is also linked to site groups, S, P, T and R in Havel's classification, but it is easier to refer to it as the GRAMED group, that is, species associated with lateritic gravel in medium rainfall.

Linking of site groups to species groups is only possible within individual classifications. Even if the nomenclature is superficially similar, eg. number (1, 2, 3, ...) or letters (A, B, C, D), the site groups sharing the same letter or number are not transferable from classification to classification.

It needs to be stressed that there is not a simple one to one relationship between species groups (indicator groups) and site groups (vegetation types or plant communities). Just as a site is the sum total of a environmental condition (water regime, nutrient regime), so a vegetation type or plant community group on a particular site is composed of several species groups responding to the environmental factors. For instance Havel's (1975a) site-vegetation type S has three main species groups associated with it: GRAMED (already discussed), FREGRA (fresh gravels) of *Macrozamia riedlei, Phyllanthus calycinus, Leucopogon capitellatus* and *Leucopogon propinquus* and DRYGRA (dry gravels) *Acacia preissiana, Styphelia tenuiflora* and *Patersonia rudis.* Although they are constantly associated with it, they are not confined to it. The GRAMED group also extends on to type P and to a lesser extent on to T and R.

The FREGRA group extends on to types Z, T, R, U and Q.

The DRYGRA group extends on to J, H, P and Z.

Expressed in words, the S type occurs on gravelly uplands in medium rainfall. The GRAMED group is centred on S, the FREGRA group extends on to it from moister, more fertile gravels, whereas DRYGRA extends on to it from drier gravels and gravelly sands.

Other species groups may also extend on to S at lower rates and less consistently such as GRAHIR (gravels in high rainfall) group of *Bossiaea aquifolium, Lasiopetalum floribundum* and *Acacia urophylla*, which is moister than FREGRA, and is mainly associated with types T and U. The HIGRA (high rainfall gravels) group of *Pteridium esculentum* and *Leucopogon verticillatus* which marginally extends on to S, but is primarily associated with types T and V, is similar to GRAHIR. The other end of the moisture / fertility continuum are *Daviesia decurrens* of DRYSAG (dry sandy gravels) and *Allocasuarina fraseriana* of SANGRA (sandy gravels), which are both centred on infertile sandy gravels or gravelly sands of types P, H, and J, but may also extend on to S. These associations are illustrated in Figure 2.1

Similar continua of species groups and site groups (plant communities or types) occur in most classifications or ordinations. The focus of this section, however, is the continuity between the various classifications. The process of establishing the continuity between the classifications is illustrated by the extension westwards on to the Blackwood Plateau.

Blackwood Plateau - Southern Swan Coastal Plain

McCutcheon 1978

The extension westward on to the Blackwood Plateau (Donnybrook Sunkland) begins with the work of McCutcheon (1978,1980), who carried vegetation studies in this region, aimed at using shrub and perennial herb species as indicators of site conditions. McCutcheon identified an array of six site types, simply labelled A, C, D, E, F and G, which were defined by 52 species. The sequence of site types reflects the common topographic and edaphic continua/catenas on the Blackwood Plateau, from leached deep sands in upland position (A), through moist sands (C) to wet alluvium on a valley floor (D) and on through moist loamy soils (E) and sandy gravels (F) to lateritic uplands (G) (Table 1). Each species was related to the site types by rating of the strength of relationship, ranging from strong positive relationship (species strongly represented on the site type) to strong negative relationship (species absent). McCutcheon presented his findings in the form of a table intended for field use, in which the species were arranged alphabetically ([redacted]

Table 1 **Relationship between site-vegetation types and environmental parameters, in a test survey area in the dry sclerophyll forest of Western Australia, expressed as a ratio of expected to observed occurrences. Ratio of 1.0 indicates lack of any relationship, major departures above or below this indicate strong positive or negative relationship. After Havel (1975b)**

Environmental parameters	Site-vegetation type							
	C	D	W	Q	R	T	S	P
Altitude zones (m)								
<213	2.8	0	0	16.5	0	4.4	0	0
213-244	2.7	0	1.3	7.8	0	4.7	0.3	0.2
244-274	2.1	0	1.1	1.3	0	2.2	1.0	0.4
274-305	1.3	1.8	1.0	0.3	1.3	0.7	0.9	1.2
305-335	0.3	1.2	1.2	0.1	1.6	0.3	1.0	1.3
>335	0	0	0	0	0	0.2	1.6	0.6
Maximum slope								
0-4° depressions	2.4	2.7	2.4	1.5	1.4	0.5	0.5	1.3
0-4° plateaus	0	0	0.1	0	0	0.9	1.7	0.4
5-8° mild slopes	0.4	0.3	0.5	0.7	0.4	0.8	1.2	1.1
> 8° steep slopes	0.3	0	0.1	1.3	2.3	2.6	1.2	0.5
Soil texture (topsoil only)								
Sand	0.4	2.5	0	0	0	0.2	0.7	2.2
Sandy loam	1.7	3.7	2.1	0.2	5.4	0.6	0.4	1.7
Silty loam	4.5	2.8	2.0	6.0	0.6	1.8	0.3	0.4
Gravelly sand	0.5	0.5	1.4	0.1	0	0.3	0.9	1.5
Sandy gravel	0.3	0.2	0.6	0.2	2.9	0.7	1.3	0.9
Loamy gravel	1.1	0	0.7	2.0	1.7	3.4	0.9	0.5

McCutcheon's criteria and sequence of site types, were retained but the sequence of species was rearranged so as to highlight the similarity of distribution within the ecological framework (Appendix F). This generated groups of indicator species, which could be related to Havel's (1975a) indicator groups. The first group of indicator species, consisting of *Banksia attenuata* and *Petrophile linearis*, is entirely confined to McCutcheon's site type A, and has strong affinities to Havel's (1975a) SANLEA (sands, leached) indicator group. Both McCutcheon and Havel associate these species with deep leached siliceous sands, which are acutely deficient in nutrients and have poor nutrient and water retention capacities. Not all of Havel's indicator species occur in Strelein's classification, as the area covered by Havel extended into a markedly drier climate than that of the Blackwood Plateau (Appendix F).

The second group of indicator species occurs on McCutcheon's site types A and C, with optimum development on C. Type C is associated with moister sandy sites in with organically enriched topsoil. The corresponding indicator group of Havel is SAMORG (sands, moist, organically enriched), which has been retained. One member of this group, *Dasypogon bromeliifolius* fits in well with McCutcheon's much larger group of indicators. The other, *Adenanthos obovatus*, has a slightly wider range, extending on to McCutcheons's site type D, of sandy swamps, and to a lesser degree to type E, of loamy swamps. McCutcheon's larger group, consisting of *Adenanthos meissnerii, Banksia ilicifolia, Daviesia incrassata, Hibbertia pachyrrhiza, Hibbertia vaginata, Melaleuca thymoides, Stirlingia latifolia* and *Leucopogon glabellus* is referred to as MOSAN (moist sands).

Another group of indicators, consisting of *Mesomelaena tetragona, Leptospermum crassipes* and *Kingia australis*, has a broader and less consistent range of occurrence centred on C and D. It corresponds to Havel's indicator group BROMO (broad tendency toward moist sites), and the name has been retained.

The group centred on McCutcheon's site types C and D, but absent from A, consists of *Banksia littoralis, Hakea ceratophylla, Melaleuca preissiana, Pultanaea reticulata* and *Hypocalymma angustifolium*. The first three belong to Havel's (1975a) indicator group VERWET (very wet sites). *Pultanaea reticulata* has not been used by Havel, and *Hypocalymma angustifolium* belongs to his indicator group FERMO (fertile moist sites). The descriptor VERWET is used to cover all five species.

The next group of indicators covers a broad range of moist site types from C to E. Only two of its members, *Meeboldiana scariosa* (formerly *Leptocarpus scariosus*) and *Pericalymma ellipticum*, have been used by Havel in his group BROWET, and to retain distinction the McCutcheon's group also consisting of *Acacia mooreana, Agonis parviceps, Dasypogon hookerii* and *Lyginia barbata*, will be named WESBROWET. Most of these species have a southwestern bias in their overall distribution.

A much narrower group of indicators of wet loamy alluvium, absent from the sandy sites A, C and D, consists of *Agonis linearifolia, Eucalyptus megacarpa, Eucalyptus patens, Hibbertia montana* (now *Hibbertia commutata*, it should be noted that *Hibbertia* montana is restricted to the Northam area), *Pericalymma elliptica* (formerly *Leptospermum ellipticum*) and *Tetratheca viminea*. The first two belong to Havel's indicator group WETAL (wet alluvium) and this name is retained, even though *Eucalyptus patens* belongs to Havel's group FERMO.

A broader group indicators, which extends over site types D, E, F and G, and consists of *Leucopogon australis, Pimelea spectabilis, Pultanaea drummondii, Hakea lissocarpha, Hibbertia quadricolor* and *Xanthorrhoea gracilis*, has no counterpart in Havel's classication and has been labelled LOSAN (loamy sands). It is the last of the groups extending on to wet and moist sites.

The next group consist of species occurring mainly on upland lateritic site types F and G, namely *Acacia browniana, Adenanthos barbiger, Allocasuarina* (formerly *Casuarina*) *fraseriana, Daviesia decurrens* (formerly *D. pectinata*), *Daviesia preissi, Hakea lasiantha, Isopogon sphaerocephalus* and *Leucopogon verticillatus*. Several of these are members of Havel's indicator groups of lateritic gravel such as SANGRA (*Allocasuarina fraseriana*), GRAMED (*Adenanthos barbiger*), DRYSAG (*Daviesia decussata*)), BROFER (*Hakea lissocarpha*) and HIGRA (*Leucbpogon verticillatus*). Others, such as *Daviesia preissii, Hakea lasiantha* and *Isopogon sphaerocephalus*, have not been used by Havel. The group is labelled WESANGRA (western sandy gravels). It has lesser climatic discrimination power than Havel's groups.

A narrower group of indicators of lateritic gravels, confined to McCutcheon's type G, contains components of Havel's indicator groups for lateritic gravels - GRAMED (*Hovea chorizemifolia, Persoonia longifolia*), FREGRA (*Leucopogon capitellatus*) and DRYGRA (*Styphelia tenuifolia, Acacia preissiana*). It also contains *Bossiaea ornata*, a species considered by Havel to have a broad range in the northern jarrah forest.

There is thus a considerable similarity between Havel's and McCutcheons's classifications. The differences reflect the difference between the Darling Plateau and the Blackwood Plateau, which has smaller edaphic and climatic range and is developed on sedimentary rather than igneous parent material. Because of these differences, some additional indicator species groups need to be added for the Blackwood Plateau, namely MOSAN, LOSAN and WESANGRA.

McCutcheon's classification also forms a natural link, both in terms of geographic proximity and botanical affinities, to the classifications of Mattiske Consulting Pty Ltd (1996) survey of parts of the Scott Coastal Plain to the south of the area surveyed by McCutcheon, and Gibson *et al.* (1994) survey of the southern Swan Coastal Plain to the west and north. However, Mattiske Consulting Pty

Ltd (1996) study also has a considerable links to Strelein's (1988) study of the southern jarrah, in particular of that portion of the study area located along the southern coast. For that reason it will be considered after Strelein. It also forms a link to Gibson's (personal communication) survey of the southwestern coast.

Gibson *et al.* 1994

There is limited overlap between McCutcheon (1978) and Gibson *et al.* (1994), as the former covers the uplands and valleys of the Blackwood Plateau, whereas the latter covers the Swan Coastal Plain below the plateau and is separated from it by the Whicher Scarp. Despite the dissimilarity in geomorphology, there is some overlap in soils and climate and hence in vegetation.

Gibson's type 2, described as southern wet shrublands, has links to McCutcheon's site-type D in *Hakea ceratophylla* and *Hypocalymma angustifolium* of McCutcheon's VERWET, *Pericalymma ellipticum* and *Lyginia barbata* of WESBROWET, *Kingia australis* and *Mesomelaena tetragona* of BROMO. These species are indicative of moist to wet sites.

Gibson's type 4, described as Melaleuca preissiana damplands, has links to McCutcheon's site-type D in *Melaleuca preissiana* and *Hypocalymma angustifolium* of McCutcheon's VERWET, *Lyginia barbata* and *Pericalymma ellipticum* of WESBROWET and *Adenanthos obovatus* and *Dasypogon bromeliifolius* of SAMORG. These species are indicative of wet sites with sandy soils.

Gibson's type 21 b, described as woodland of *Banksia attenuata* and *Eucalyptus marginata* subsp *marginata*, has links to McCutcheon's site-type A in *Banksia attenuata* and *Petrophile linearis* of McCutcheon's SANLEA, *Stirlingia latifolia, Melaleuca thymoides* and *Hibbertia vaginata* of MOSAN and *Dasypogon bromeliifolius* of SAMORG, most of which are associated with sandy soils that are drier than those of Gibson's type 2.

Gibson's type 22, described as woodland of *Banksia atten*uata and *Banksia ilicifolia*, has links with McCutcheon's type C in *Banksia attenuata* and *Petrophile linearis* of McCutcheon's SANLEA, *Banksia ilicifolia* of MOSAN, *Dasypogon bromeliifolius* of SAMORG, *Melaleuca preissiana* of VERWET and *Lyginia barbata* of WESBROWET, most of which are associated with moist sandy soils.

Gibson's types 21 b, 22 and 4 form a gradient from dry to wet sandy sites which has a close parallel in McCutcheon's gradient from site-type A through C to D and in continuum segments H, I, J and K described from the northern Swan Coastal Plain by Havel (1968). Gibson's type 2 represents a heavier-textured variant of type 4.

Gibson's type 3 b represents heavier-textured equivalent of Gibson's type 22. It consist of woodland of *Corymbia calophylla* and *Eucalyptus marginata* subsp *marginata*, with understorey of *Kingia australis, Mesomelaena tetragona, Xanthorhoea preissii, Bossiaea eriocarpa* and *Hibbertia hypericoides*. It has a weak link to McCutcheon's site-type C in *Kingia australis* and *Mesomelaena tetragona* of BROMO.

As anticipated, the linkage between McCutcheon (1978) and Gibson *et al.* (1994) is limited, but the distribution of species along the moisture gradient is parallel for both classifications.

Southern Jarrah - Scott Coastal Plain – Coastal Dunes

The linkage process was also carried through in a south westerly direction from the northern jarrah forest into the southern jarrah forest classified by Strelein (1988), further on to the Scott Coastal Plain mapped by Mattiske Consulting Pty Ltd (1996) and finally to the coast of the Southern Ocean classified by Gibson (personal communication).

Strelein 1988

Strelein's (1988) classification of the southern jarrah forest is a valuable link with other classifications because of the similarity of his concepts and methods used in the northern jarrah forest, and the thoroughness with which he tested his indicator species.

Strelein (1988) used similar nomenclature to Havel (1975a), namely letters of alphabet to define site-vegetation types described in terms of indicator groups and underlying environmental factors. Some of his types are very close to Havel's types.

The linkage process is described in Appendix F. On the whole, the linkage of Strelein's (1988) classification to that of Havel (1975a) is strong. What differences there are can be primarily attributed to the following factors:

1. Cooler and moister climate of the southern jarrah
2. Concentration by Strelein on sites dominated by jarrah (*Eucaluptus marginata*), which excluded most of the fertile dissected slopes in the high rainfall zone.

The shift into a cooler and moister climate has resulted in the shift in the indicator value of some species and groups. Generally the narrow indicators of the high rainfall became more general in their distribution, those of medium rainfall zone became more restricted and many of those of the northern low rainfall/high evaporation zone disappeared altogether. By contrast, many new species with bias toward cool moist climate entered into the picture.

To account for these differences, a number of new indicator groups had to be defined, such as SOGRAF, SOGRA, SOSALOM, SOSAM, SOWET, SOFER and SOBROSAN.

Mattiske Consulting Pty Ltd 1996

Mattiske Consulting Pty Ltd (1996) data set consists of a larger number of species, as there was a requirement to cover the diversity of species in the studies. In delineating the vegetation mapping units comparisons can be made between the latter data and the findings of McCutcheon (1978,1980) and Strelein (1988). The latter comparison was feasible, as a record of the distribution of all the species on the 27 vegetation types identified by the study. In re-interpreting this data, only a portion of the data set (148 species), chiefly perennial species encountered in other data sets, has been utilised but retaining those identified as being of special significance to the Scott River Plain have been retained.

The description of the classification, and of the linkage process are covered in Appendix F.

Summing up, there is a considerable linkage between Mattiske Consulting's, Strelein's, McCutcheon's and Havel's indicator species groupings, but overall the vegetation described by Mattiske Consulting is at the wet end of the regional continuum.

Gibson 1997 (unpublished)

Mattiske Consulting (1996) classification forms a natural link between the classifications so far discussed and that of Gibson (personal communication), which was confined to the southern and western coast. The linkage is directly to Gibson's communities, without defining species groups (Appendix F).

The linkage between the two classification is largely confined to the swampy sites, as Mattiske Consulting did not survey coastal dunes and Gibson avoided inland forests, which he considered covered by earlier classifications.

Gibson *et al.* 1994 and Mattiske Consulting Pty Ltd 1996

Although there is no geographic overlap between the areas covered by Mattiske Consulting Pty Ltd (1996) and Gibson *et al.* (1994), there is considerable ecological similarity between the Scott Coastal Plain surveyed by Mattiske Consulting and the southern end of the Swan Coastal Plain surveyed by Gibson *et al.* (1994), both of which border the Blackwood Plateau. The main difference is that whereas the Scott Coastal Plain merges almost imperceptibly into the mildly sloping southern edge of the Blackwood plateau, the Swan Coastal Plain is separated from the northern edge of the plateau by the moderately steep Whicher Scarp. However, away from the scarp the Swan Coastal Plain also incorporates near-level poorly drained plains and swamps, which characterise the Scott Coastal Plain, though the latter has a significantly wetter and cooler climate. Consequently there is a greater degree of linkage between Mattiske Consulting (1996) and Gibson (1994), than between Gibson (1994) and McCutcheon (1978), despite the geographic proximity of the latter two.

The integration of the south western classification is summarised in Appendix F. Only multiple entry species, that is, species identified as significant (indicators, characteristic species) by two or more classifications were entered. Mattiske Consulting Pty Ltd's (1996) classification was used as the starting point as it has the widest range of species and widest range of sites. Havel's 1968 and 1975a classifications were used as links to the northern jarrah forest and northern coastal plain.

Southern Jarrah - Karri – Walpole National Park – Tingle Mosaic – Coastal Dunes

The ease of southward extension into the area covered by Christensen (1980) (southeastern jarrah and wandoo), Strelein (1988) (southern jarrah and wandoo) and Inions *et al.* (1990a,b) (karri) varies markedly. Christensen (1980) was primarily interested in vegetation as a setting for fauna studies and did not develop his classification to the same degree of detail as that of Strelein (1988), with which it overlaps. Both followed the methodology of Havel (1975a) closely, and as the main tree species are also shared with Havel, the agglomeration can be expected to be relatively easy. By contrast Inions *et al.* (1990a,b) focused on a different species and utilised a radically different methodology, so that integration with other classifications or ordinations may prove difficult. His coverage complements that of Strelein, in that both covered a comparable climatic region, but different landforms within it. The strategy adopted here is therefore to establish links between the classifications of Strelein and Havel and to use Strelein's classification as a bridge to Christensen and Inions *et al.*(1990).

Christensen 1980

Christensen's (1980) classification, though predating that of Strelein (1988) is best dealt with as a supplement to it. In terms of the area covered it is largely a northeastern subset of Strelein's, and because of its focus on fauna it lacks the detail of Strelein's analysis of individual species and definition of site types. Nevertheless it can be used to add to Strelein's classification. In Christensen's ordination the extreme +C3 defines a treeless shrubland on shallow soils over granite, dominated by *Gastrolobium spinosum, Dryandra armata, Baeckea camphorosmae, Hakea undulata* and *Hakea incrassata*, which is more droughty than any of the types described by Strelein and fits outside Strelein's types Z and M. It is equivalent of Havel's (1975b) type G. Similarly, in Christensen's ordination the extreme +C2 and +C4 define a jarrah woodland with a shrub storey of *Petrophile serruriae, Hibbertia quadricolor, Banksia sphaerocarpa, Pimelea suavolens, Pultanaea ericifolia* and *Leucopogon pulchellus*, which also fits outside Strelein's type Z, on the sandier, less fertile side. Its northern equivalent is Havel's (1975a) type H.

One of Christensen's major sampling localities consisted of a cluster of sites in which *Eucalyptus wandoo* was a dominant, rather than an associate of *Eucalyptus marginata*. It occurred on heavy textured soils and had a shrub storey of *Hypocalymma angustifolium, Acacia pulchella, Leucopogon pulchellus* and *Dryandra lindleyana (*formerly *nivea*). It lies on the outside of Streleins types M and Y, and is the southern equivalent of Havel's (1975a) type Y. In Christensen's ordination it fitted in at +C1 and +C2.

The remaining vegetation types described by Christensen are covered by Strelein's classification. The -C2 extreme of Christensen's ordination coincides with his westernmost sampling locality, and carries a tall open jarrah forest with shrub storey of *Bossiaea linophylla, Hovea elliptica* and *Clematis pubescens*, which links it with Streleins types T, Q and U. Like them, it occurs on fertile slopes in medium to high rainfall. The -C4 extreme of Christensen's ordination consists of woodland of *Melaleuca preissiana, Banksia littoralis* and *Eucalyptus rudis*, with an understorey of *Astartea fascicularis* and *Melaleuca viminea*. Its closest associates are thus Strelein's type A and Havel's (1975a) type A, and like them, it occurs on poorly drained, swampy valley floors.

Inions *et al.* 1990a and 1990b

As briefly mentioned above, Inion's *et al.* (1990a,b) classification represents a radical departure, both in terms of the dominant species (karri -*Eucalyptus diversicolor*), age of the stand (regrowth following clearfelling), methodology (agglomerative hierarchical cluster analysis and discriminant analysis) and terminology (community types numbered and also named after former prominent foresters).

Nevertheless, it is possible to link it to Strelein's (1988) classification to some degree, because the two classifications refer to the same geographic region, their coverage of landforms is complementary and there is an overlap at the margins, generally on sites of below average fertility and above average drought risk for karri. It is important to recognise that the presence of karri is assumed in all of Inions *et al.*'s community types, which only differ in the associates of karri.

The full description of the linkage process, which includes description of the site groups and species is given in Appendix F.

The difficulty of relating Inions *et al.*'s classification to that of Strelein arises from the fact that apart from a few shared transitional types, the two classifications look in opposite directions. Species that are common in the jarrah forest have been identified by Inions *et al.* as strong indicators of inferior karri sites, being departures from the karri norm. Similarly, species that are common in the karri forest have been identified as strong indicators of superior sites within the jarrah forest by Strelein, being departures from the jarrah norm.

Bridgewater 1981

The relationship between Strelein's (1988) classification of the southern jarrah forest and Inion's (1990b) classification of the karri forest can be elucidated by examining the study of Bridgewater (1981) from the interface between karri and jarrah forest near Pemberton. Bridgewater was demonstrating the applicability of the Zurich-Montpellier methodology (Braun-Blanquet) to Australian conditions. He located his relevés along a 5km gradient spanning the two forest type and arranged them into a relevé/species matrix according to their floristic similarity. He grouped the relevés into six groups, each defined by several sets of species. Two of the relevé groups contained jarrah (Eucalyptus marginata) and no karri (*Eucalyptus diversicolor*), two contained karri and no jarrah, whereas the two intermediate groups contained predominantly karri but with some jarrah. The two jarrah groups and the two intermediate groups also had a strong development of large tree species *Corymbia* (formerly *Eucalyptus*) *calophylla*, understorey tree *Allocasuarina* (formerly *Casuarina*) *decussata*, tall shrub *Bossiaea laidlawiana*, fern *Pteridium esculentum*, and climber *Clematis pubescens*. *Chorilaena quercifolia* had a range similar to karri. The jarrah groups had a set of tree, shrub and herb species largely confined to them, namely *Persoonia longifolia, Lindsaea linearis, Logania vaginalis, Acacia drummondii* and *Billardiera floribunda*. Similarly, one of the karri groups had two species, *Trymalium floribundum* and *Acacia urophylla*, largely confined to it. Two other species used by Strelein and Inions *et al.* in their classifications, *Leucopogon verticillatus* and *Crowea angustifolia*, occurred inconsistently across the whole range. On the basis of the indicator species, the range appears to extend from Strelein's type T through K and N to Inions *et al.*'s community types Beggs and Shea. Depending on which of Bridgewater's set of species was considered, the entire range could be seen as a continuum or as a number of distinct types. The range or continuum could be expanded in one direction to cover all of Strelein's jarrah types, and in the other direction to cover all of Inions *et al.*'s karri types.

Wardell-Johnson *et al.* 1989

The departure from the northern jarrah framework reaches the maximum with those classifications centred on the south coast, namely Wardell-Johnson *et al.* (1989), Wardell-Johnson *et al.* (1995) and Gibson (personal communication). There is some overlap between Wardell-Johnson *et al.* (1989) and Strelein (1988) and Inions *et al.* (1990b), and this will be explored. Wardell-Johnson *et al.* (1989) is essentially a subset of Wardell-Johnson *et al.* (1995), but will be considered because it gives considerable attention to indicator species. Both overlap to some degree with Gibson (personal communication), which is essentially a coastal classification.

The details of the linkage process, and description of the site groups and species groups, are given in Appendix F.

Wardell-Johnson *et al.*'s (1989) classification, whilst covering a relatively small area of land on the south coast, is important in that it provides linkage from the classifications of Inions *et al.* (1990b) and Strelein's (1988) to the classifications of Wardell-Johnson *et al.*'s (1995) and Gibson (personal communication). The overlap with Strelein and Inions *et al.* is mainly in open forest and high open forest formations. Wardell-Johnson *et al.*'s (1989) community types and characteristic species groups are generally broader than those of Inions *et al.* (1990b) and Strelein's (1988), chiefly because only twelve types are used to describe a wider ecological range. In the terms of area coverage and of total ecological amplitude it is a subset of Wardell-Johnson *et al.*'s (1995), but gives more attention than the latter to indicator (characteristic) species.

Gibson (personal communication) covers a very long but also very narrow strip along the entire coast of the RFA project from the northwest to the southeast, and Wardell-Johnson *et al.*'s (1989) types 9-12 have a strong affinity with those of Gibson's (personal communication).

Wardell-Johnson *et al.* 1995

However, the key to understanding the plant ecology of the Warren bioregion is Wardell-Johnson *et al.*'s classification (1995), because it is not limited to a particular forest type or geomorphic surface and covers an extensive and diverse area. It has limitations. It is difficult to interpret floristically, as the thirteen groups of indicator species, corresponding to twelve community type level, are obviously influenced by the disparity, in both size and uniformity, of the community types. At one extreme there are large but uniform community types such D1, D2 and E1, each of which contains in excess of 60 plots and yet are floristically simple and edaphically homogeneous. At the other extreme there are small but diverse groups such as C1, C2 and C3, each of which contains less than 15 plots and yet are floristically diverse and edaphically heterogeneous. The species group derived by the analysis vary from few large groups too heterogeneous to be of use as indicators, through some medium size groups with well defined ecological affinities to small groups associated narrowly with just a few plots. Overall, they are of limited use.

The problem of flawed species groupings was experienced by Havel (1975a) when using classificatory programs in the northern jarrah forest. In the case of monothetic divisive classification using the DIVINF program (Lance and Williams 1968) the heterogeneous groups were the product of long chain of negative decision, which lumped together uncommon species of diverse site preferences. In the case of polythetic agglomerative classification using the program CLASS (Lance and Williams 1967), the normal analysis produced sound grouping of plots, but the inverse analysis produced both very large heterogeneous groups of species and small groups of just one or two species. Similar problem in the use of classification programs was experience by Young and Watson (1970). In the case of Wardell-Johnson *et al.* (1995) this problem was aggravated by the inbalance between few plots from the low rainfall areas as compared to a very large number from the high rainfall areas, and by the contrast between floristically simple and uniform plots from forested uplands and floristically diverse plots from extreme edaphic sites such as rock outcrops and swamps.

At the finer level of definition (44 community subtypes), which is closer to the level of definition of Strelein (1988) and Inions *et al.* (1990b), no species groups have been derived. However, a comprehensive list of species for the 44 types has been made available for this study and has been subjected to the Zurich-Montpellier type of analysis like that carried out for the jarrah-karri ecotone by Bridgewater (1981). The definition and sequence of community subtypes given by Wardell-Johnson *et al.* (1995), has been retained but the species have been rearranged using the indicators defined by Havel (1975a), Strelein (1988), Inions *et al.* (1990b) and Wardell-Johnson *et al.* (1989), as the condensation nuclei. To make the rearrangement feasible, the analysis has been limited to those species which reached a constancy of 50% or higher within at least one community subtype. The resulting matrix (44 subtypes x 381 species) depicts the usual pattern of lumpy continuum encountered in other studies of south western vegetation, but has an unusually high number of singletons (site group with only one member). Forty-two indigeneous species groups and one exotic species groups have been defined. As many can be readily related to the species groups defined by Havel (1975a), Strelein (1988), Inions *et al.* (1990b) and Wardell-Johnson *et al.* (1989), they were given mnemonic labels reflecting their similarity, though not equivalence, to the groups based on the work of these authors. Most of the indicator species identified by these authors are represented in the matrix. Additional mnemonic names, reflecting the known or assumed links to environmental factors, were also generated to accommodate the broader ecological range of Wardell-Johnson *et al.* (1995) data set. As in the case of Havel's (1975a) studies in the northern forest, the more extreme sites of Wardell-Johnson *et al.* (1995) classification, such as his community groups 13, 19 and 25-32, have a narrow and precise set of species, whereas the intermediate sites 2-9 and 37-42 are loosely defined by several sets of species with broad environmental tolerances. Correspondingly, a species with narrow environmental range such as *Pimelia longiflora* and *Leucopogon glabellus* of the EXSAN group are confined to just one or two community groups. A species with broad environmental range, such as *Agonis parviceps* of SOSALOM is prominent on 14 of the 44, and *Leucopogon capitellatus* of BROMOF on 18 out of 44 community groups of Wardell-Johnson *et al.* (1995).

The full species / site matrix, and the description of the linkage process, is given in App. 2.6. The relationship between WJ 95 and Strelein classifications can be summarised as follows: There are quite strong matches between them involving species characteristic of the jarrah (*Eucalyptus marginata* subsp *marginata*) forest. In both classifications there is a continuum in moisture and fertility from infertile sands to moderately fertile loams, involving such species groups as SAMORG, SOWET, DRYGRA, SOGRA, SOGRAF, FREGRA, HIGRA, SOFER and SOFERMO. However, many of the species groups of WJ 95 which are characteristic of extreme sites such as coastal sand dunes, deep swamps and rock outcrops have no counterpart in Strelein, who was primarily concerned with the southern jarrah forest.

The relationship between the classifications of Wardell-Johnson *et al.* (1995) and Inions *et al.* (1990b) is influenced by the fact that Inions *et al.* covered regenerated stands of karri (*Eucalyptus diversicolor*) over a great geographic range, but excluded other vegetation types, whereas Wardell-Johnson *et al.* (1995) covered all vegetation types over a more limited, and only partially overlapping geographic range. There is thus no match in the Inions *et al.* classification for most of the species groups defined by us in Wardell-Johnson *et al.* 1995's species/subtype matrix, particularly those of extreme sites such swamps and rock outcrops. There is, however, a good linkage for tall open forest of karri. On the whole there is thus only localised correspondence between Wardell-Johnson *et al.* (1995) and Inions *et al.* (1990b).

Localised correspondence was also found between Wardell-Johnson *et al.* (1995) and Gibson (personal communication), as Gibson's study was focused on coastal dunes and nearby swamps, avoiding forests which are the main focus of Wardell-Johnson *et al.* However, within the coastal sand dunes and swamps of the southern coastal plain, there is a good correspondence between Wardell-Johnson *et al.* (1995) and Gibson (personal communication).

The ultimate stage of comparing the various vegetation classifications and ordination in the Jarrah and Warren bioregions is to assess whether there are groups of species that co-occur together under similar edaphic and/or climatic conditions, across the various classifications.

The Wardell-Johnson *et al.* (1995) classification of the Tingle Mosaic has been used as the framework for such integration in the eastern portion of the Warren bioregion, as it has the widest ecological range, the greatest number of individual species, and in addition has geographical overlap with most other classifications. It is also based on the largest set of field plots, and has sound statistical definition of community types, which in turn form the basis of the species group definition.

The process has taken ecological groups within the Wardell-Johnson *et al.* (1995) classification and has compared them species by species with the other classifications (Wardell-Johnson *et al.* 1989;

Gibson personal communication; Strelein 1988; Inions *et al.* 1990a,b; Christensen 1980; Havel 1975a). Havel (1975a) has been included as linkage with classifications in the Jarrah bioregions, even though it does not have a geographic overlap with Wardell-Johnson *et al.* (1995). An example of the higher level linkage process is given below.

One of the more extreme community types within Wardell-Johnson *et al.*'s (1995) classification is community type 1. It is composed of plots situated on extreme sandy sites, with a high degree of leaching and infertility. It is primarily defined by the species groups EXSAN and DRYSAN, in fact the EXSAN group occurs on this type alone. Of the EXSAN species with fidelity in excess of 50 %, four also occur in other classifications:

> *Pimelea longiflora* subsp *longiflora* is a key characteristic species in the PIMLONG group of Wardell-Johnson *et al.* (1989), and also occurs in Gibson's (personal communication) community group 14, *Bossiaea rufa* also occurs as characteristic species of Gibson's (personal communication) community group 13. *Daviesia decurrens* is also a member of Havel's (1975a) indicator group DRYSAG. *Leucopogon glabellus* is also a member of McCutcheon's (1978) group MOSAN.

Although *Banksia attenuata* does not reach the 50% fidelity criterion in community type 1, it is often the structurally dominant tree species of this type and of Gibson's (personal communication) community groups 14 and 15. It is a common associate of *Daviesia decurrens*. The remaining species of the EXSAN group, namely *Petrophile longifolia*, and *Hypocalymma strictum*, do not feature in the other classifications, but that does not necessarily mean that they are absent in the areas covered by them.

The species group DRYSAN is mainly, but not exclusively, confined to Wardell-Johnson *et al.*'s (1995) community types 1 and 2. Of its component species, three also occur in other classifications:

> *Lyginia barbata* is also a member of Wardell-Johnson *et al.*'s (1989) PIMLONG group and is a characteristic species of Gibson's (personal communication) community groups 10, 14 and 30. *Melaleuca thymoides* is member of SOSAM group of Wardell-Johnson *et al.* (1989) and Strelein (1988) and is a characteristic species of Gibson's (personal communication) community groups 10, 14, 15 and 30. *Allocasuarina fraseriana* is a characteristic tree species in Wardell-Johnson *et al.* (1989) and Havel's (1975a) SANGRA group. *Hakea ruscifolia* is a member of the SOSAM group of Strelein (1988) and DRYSAG group of Havel (1975a). Although *Banksia ilicifolia* does not reach the 50% fidelity criterion in community type 2, it is often the structurally dominant tree species of this type and of Gibson's (personal communication) community groups 14. The DRYSAN group is indicative of less extreme sandy sites than EXSAN.

The next species group, BROGRA, has much greater ecological amplitude than either EXSAN or DRYSAN, extending across Wardell-Johnson *et al.*'s (1995) community subtypes 1 to 10, and being absent from community subtypes 11 to 17 (coastal dunes), 18 to 25 (swamps) and 26 to 30 (rock outcrops). It reappears in community subtype 31 and 39-41 (lateritic uplands), but is again absent from subtypes 42 to 44 (karri forest), and is thus essentially composed of species of the jarrah forest, including jarrah itself. The component species are common in other classifications. *Eucalyptus marginata* subsp *marginata* occurs in Gibson's (personal communication) community groups 14, as do *Anarthria scabra* and *Andersonia caerula*. *Eucalyptus marginata* subsp *marginata* also enters into the DRYKA species group of Inions *et al.* and Wardell-Johnson *et al.* (1989), and is so prevalent in Strelein's classification of southern jarrah as to have only a negative indicator value (NEGIN), that is, it is only absent from the most extreme sites. The same is also true of *Persoonia longifolia*. In Havel's classification of northern jarrah *Eucalyptus marginata* fits into a category of its own (JARRAH), which also has a very wide ecological amplitude. *Persoonia longifolia* is a key species of ecological species group GRAMED in Inions *et al.* (1990b) and Gibson's (personal communication) community groups 14, as is *Agonis hypericifolia*. Another species of very wide amplitude is *Xanthorrhoea preissii*, which is included in Inions *et al.*'s (1990b) and Wardell-Johnson *et al.*'s (1989) species group BROMO and Gibson's (personal communication) community groups 20 and 30. *Lindsaea linearis* is a member of Wardell-Johnson *et al.*'s (1989) species group JACFUR. The BROGRA species group is thus essentially a ecological species group of broad amplitude covering the jarrah forest on coarse grained and infertile soils, such as sands and sandy gravels. The details of the higher level linkage process are given in App. 2.7. The outcome of the process is shown in Table 2.4.

The association (grouping) of species varies from study to study, as each study was carried out from different perspective and in a different area, but the relationship of the species groups to environmental factors on the whole holds good, that is basically the same species are associated with particular set of environmental conditions:

> *Pimelia longiflora, Lyginia barbata, Melaleuca thymoides* and *Allocasuarina fraseriana* are associated with extremely infertile sandy sites,
>
> *Eucalyptus marginata, Persoonia longifolia* and *Agonis hypericifolia* with infertile gravely sites,
>
> *Adenathos obovatus* and *Dasypogon bromeliifolius* with moist humus podzols,
>
> *Homalospermum firmum, Anarthria prolifera* and *Beaufortia sparsa* with swamps and
>
> *Acacia urophylla, Clematis pubescens, Eucalyptus diversicolor* and *Pteridium esculentum* with finer textured and more fertile soils.

Some of the species have consistent association with one another, such as *Dasypogon bromeliifolius* and *Adenanthos obovatus* of SAMORG and *Agonis flexuosa* and *Anigozanthus flavidus* of SOBROSAN. Other association between species, especially those based on joint occurrences in ecotones such as the Harris (No 5) community type of Inions *et al.* (1990b) and community types No 4 and No 5 of Wardell-Johnson *et al.* (1989), are unstable and vary from classification to classification. For instance, the characteristic species described for community type No 5 of Wardell-Johnson *et al.* (1989) (*Acacia browniana, Agonis parviceps, Bossiaea webbii, Burchardia umbellata, Leucopogon australis, Pimelia longiflora, Stylidium scandens* and *Xanthosia rotundifolia*) are brought together because the type represents an ecotone between *Agonis parviceps* shrubland and forest with *Acacia browniana* understorey, developed over a wide range of soil types. They form different associations in other classifications.

It is apparent from the above discussions that the various local classifications within the Warren bio-region (southern subregion) are mutually linked though the linkage is not a case of one-to-one correspondence. They are also linked, chiefly through Strelein (1988) to the Jarrah bioregion.

Northern Jarrah - Collie Basin - Wandoo Woodlands

The classification covering the bulk of the subregion (Havel 1975a,b) is used as the basis for the linkage, as it has the widest ecological as well as geographical coverage. Its linkage to E.M. Mattiske and Associates (1991) classification of the Collie Coal Basin is strong for those of Havel's species groups and site groups characteristic of sands and sandy gravels, but weak with those charactistic of loamier, more fertile soils of the major valleys in crystalline terrain. Mattiske Consulting used a comparable classification to that of Havel, refined to a greater detail (A A1, A2, A3, S S1, S2, S3) for the prevalent types.

Worsley Alumina Pty Ltd's (1999) has strong linkage to Havel (1975a,b) in the types characteristic of uplands and valleys of crystalline terrain in medium to low rainfall. The linkage is weak to types developed on sedimentary deposits, which are largely absent in Worsley's project area. The linkage is reinforced by similarity of classification, refined in greater detail for rocky sites (G G1, G2, G3, G4).

The earlier maps and classifications of Worsley Alumin's Pty Ltd (1981,1985) employ a radically different nomenclature which reflects structire as well as floristic composition, but this is relatively readily linked with that of Havel (1975a,b), namely

Havel (1975a,b)	**Worsley Alumina 1985**
P, SP, Z	19JLc
S, ST	19Bg, 19JSd
M, Y, L	11W
G	21Aah, 24HCg
D, J	19JMr
AY, A	23HDc

Loneragan (1978) did not attempt to relate his findings to Havel's (1975a) site-vegetation types, though this is relatively easy to do so for the tree data. In the wandoo dominated clusters TG1 is largely equivalent to Havel's types Y and L and T3 to M. Similarly in the jarrah dominated clusters TG5 represents Havel's types R and T and TG6 represents mainly P, H and S. Loneragan's TG2 has similarity to Havel's type M, but warrants a separate category, as it occurs largely outside the area sampled by Havel and is distinguished from M, Y and L by the dominance of powderbark wandoo, *Eucalyptus accedens*. Only the highly polyspecific and geographically widespread T4 cluster is problematic. It is more difficult to relate Loneragan's understorey species groups based on common species to Havels' indicator groups based on species selected for their discriminatory capacity, (Appendix F).

The linkage to Ecologic Environmental Consultant's (1994) survey of the wandoo woodlands is affected by the fact that wandoo is central to the Ecologia's studies, but peripheral to Havel's classification and mapping. The geographical overlap is only partial. Nevertheless, there is considerable sharing of species and species groups. Ecologia's communities 1 and 2 resemble Havel's types Z, H and P, community 3 resembles M and 5 resembles Y and L. Ecologia's community 4 has definite links with G and community 6 has a link to A and AY.

The linkage is even more tenuous between Griffin's (1992) classification of the northern most tip of the RFA region and that of Havel's (1975a,b) due to complete lack of geographic overlap, and the differences in the degree of detail of Griffin's revelee groups 35, 43, 44, 40 and 41 describe lateritic uplands comparable edaphically but not climatically to Havel's types SP and S. Climatically, a better match for lateritic uplands is between Havel's Z and Griffin's 7. On the shallow rocky sites Griffin's 38, and to a lesser degree 9 and 4, match Havel's G. On the sandy sites, there is a much clearer equivalence between Griffin's relevees groups 2 and Havel's types B and J. Similarly, on the swampy sites there is a strong linkage between Griffin's 15 and 27 and Havel's A and AY.

There are also coarse but strong linkeages between Heddle and Marchant (1983) and Havel (1975a,b). Heddle and Marchant's structural category JMOF (jarrah-marri open forest) corresponds to Havel's types P, S and T, and their category WMW (wandoo-marri woodland) corresponds to Havel's types M, L and Y. Heddle and Marchant's mix of healthy and shrubby categories (H, HB, HT, RSLW) corresponds to Havel's types G and R. The summary of the linkeages is given in Appendix F.

Basically the strength of linkages between the carious classifications of the Jarrah brioregion is governed by ecological overlap. Havel's (1975a,b) classification and mapping is linked to E.M. Mattiske and Associates (1991) on infertile gravelly and sandy sites, to Worsley Alumina Pty Ltd (1985,1999) on eastern woodlands and heaths, to Ecologia (1994) on eastern woodlands, heaths and swamps, to Griffin (1992) opn northern woodlands and to Heddle and Marchant (1983) on north western forests, woodlands and shrublands.

Summary of linkages over the entire RFA region

Althoough the classifications at the extremes of the range, such as that of Gibson (personal communication) on the wet and cool south coast and Ecologia (1994) on the dry north eastern periphery do not have much in common, they are nevertheless part of a continuum. The classifications that are ecologically broader and geographically more extensive, such as those of Wardell-Johnson *et al.* (1995), Strelein (1988) and Havel (1975a) between them cover the middle of this continuum. The linkages are not solely dependent on geographical proximity. The species groups characteristic of the more extreme site conditions, such as deep leached sands, shallow rocky sites and seasonal swamps recur on these sites irrespective of distance, often spanning major discontinuities. On the less extreme and more common sites, such as the well drained lateritic uplands, there is a progressive change from south west to north east, which is barely detectable in the middle of the climatic continuum, but clear cut between the extremes. The clearest and most rapid rate of change along the climatic continuum is on moderate valley slopes with fertile soils of medium depth. Even the districts not covered by any publications, such as the Margaret River Plateau and the Blackwood catchment east of the Darling Scarp, largely appear to fit within this continuum.

The task that remains is to convert the knowledge acquired by the reviewing the existing classifications to vegetation, and the available climatic and geomorphic framework, into a workable mapping scheme. The first step toward that objective is to firm up the relationships between vegetation and the environment. The second step is to use these relationships to fit vegetation into the environmental framework of climate and landform.

Vegetation Mapping of the South West Forest Region.
Part 5: Vegetation Mapping Classifications

Development of Methodology

The methodology of the mapping at a bioregion scale was reviewed earlier, and it was concluded that the most appropriate approach was the recent North American combination of broadscale environmental framework within which the finer scale vegetation patterns are fitted. On the basis of review of past classification studies it was also concluded that the continuum model was the most appropriate one for the local situation. The essence of this is that vegetation varies continuously, but that it also is possible to subdivide it by focussing on species that have narrower ranges and are responsive to environmental factors. As the next step, the environmental framework of climate and landform was established. Finally, the earlier classifications were tested for continuity and linkages, and it was established that many key species (indicators, characteristic species) were shared between them. These species formed species groups that could be referred to similar environmental combinations. It is now proposed to link the environmental factors, in particular climate and landform, into a framework to examine the relationships between vegetation and the environment in greater depth and to utilise these relationships to fit the fine scale vegetation patters into the broadscale environmental framework.

Climate

For the purpose of mapping, Gentilli's (1989) climatic criteria were modified for plotting as a single parameter by using the summer evaporation to discount the annual median rainfall. The rate of discounting that was found to reflect vegetation pattern was to reduce the median rainfall by 100 mm for every 50 mm increase in summer evaporation. The total range of the discounted median rainfall was subdivided into climatic subzones of 200 mm width. Gentilli's terminology was used to describe the full range from 1200+ mm rainfall/less than 400 mm evaporation (hyperhumid) to less than 500 mm rainfall/ 800+ mm evaporation (perarid). The terminology adopted may not fit in with terminology for all of Australia as there are climatic zones both wetter and drier than those dealt with here.

An alternative method of combining the annual rainfall with summer evaporation into a single parameter is to express them as a ratio. This parameter ranges from more than 3 for the hyperhumid south coast to less than 0.66 for the perarid northeast.

The relationship between annual median rainfall and summer (December to February) evaporation is considered to be the broad-scale determinant of regional vegetation patterns. It is modified locally by topographic and edaphic factors, in particular by their effect on the storage of the winter rainfall toward the summer water stress. The range extends from steep rocky slopes with shallow soils, from which the incoming rainfall is shed almost immediately through milder slopes with deep soils capable of storing the bulk of the winter rainfall, to level depressions which receive runoff from the surrounding uplands and are flooded or waterlogged for a significant portion of the winter and spring seasons. This aspect will be discussed in greater detail in the section dealing with the relationship between vegetation, geomorphology and climate.

Geomorphology

Systems

The vegetation systems mapped here, at the scale of 1:500,000, are close to Tille's (1996) land systems in the terms of concept, though not of scale, in that the polygons are smaller and the texture of the map is finer. This was done so that the whole project area could be displayed on one map sheet and the overall control of climate over the vegetation patterns illustrated. Although the vegetation complexes are mapped at a comparable scale of 1:250,000, the definition, in terms of geomorphology and climate is finer, being more comparable to Tille's (1996) subsystems.

Subsystems

The vegetation complexes are of comparable scale and degree of detail, in terms of landforms, to Tille's subsystems particularly in the northern portion of the project area. In the southern two-thirds of the project area, where landform mapping has been more precise, they correspond to Tille's phases.

Phases

The maps of vegetation complexes are dependent on the landform maps, though the detail mapped at 1:50,000 (Tille and Lantzke 1990; King and Wells 1990) for phases could not always be accommodated in the vegetation complex maps at 1:250,000.

At the other end of the scale the larger units, such as Bevan, which extend across several climatic zones, were subdivided into subsystems based on climate, such as

BE1 southern lateritic uplands in perhumid-humid zones
BE2 southern lateritic uplands in humid-subhumid zones
BE3 southern lateritic uplands in subhumid-semiarid zones

Similarly, in the northern Darling Range the equally extensive Dwellingup unit was subdivided into:

D1 northern lateritic uplands in the humid-subhumid zones
D2 northern lateritic uplands in the subhumid-semiarid zones
D3 and D4 northern lateritic uplands in the semiarid to arid zone.

Integration of Climate and Landforms

During the latter subdivision of the coding systems for the vegetation complexes, the components of the vegetation were used as the basis of the subdivision. In order to minimise fragmentation, the subdivision of upland systems was carried along drainage lines and subdivision of valley systems along crest of divides, rather than isohyets – hence the fuzziness of the climate definition.

In the case of the more highly structured classification systems, such as Tille's (1996) Wellington-Blackwood, the climatic zoning was already partially built in by differentiating between the Western and Eastern Darling Range Zones and the Warren-Denmark Zone, within which the lateritised uplands were named Dwellingup and Hester; Dalmore and Sandalwood; and Bevan and Mattaband, respectively.

The importance of the climatic subdivision of the landforms can be seen in the case of such a widespread landform as Wheatley, which is described by Churchward (1992) as upstream valleys incised 20-40 m into the southern Darling Plateau. In the perhumid zone near Pemberton (WH1), the vegetation of the slopes is a karri-marri tall open forest with a second storey of *Allocasuarina decussata, Agonis flexuosa, Banksia grandis and Persoonia longifolia*, and a tall shrub storey of *Trymalium floribundum, Tremandra stelligera, Hovea elliptica, Bossiaea aquifolium* subsp. *laidlawiana, Lasiopetalum floribundum, Clematis pubescens* and *Pteridium esculentum*, corresponding to Inions *et al.'s* (1990 a and b) types 5, 9 and 10. In the humid-subhumid zone immediately east of Manjimup the slopes of the same landform (WH 2) support an open forest of marri, yarri and jarrah, with a second storey of *Banksia grandis, Persoonia longifolia, Agonis flexuosa* and *Hakea oleifolia* and understorey of *Trymalium floribundum, Tremandra stelligera, Hovea elliptica, Bossiaea aquifolium* subsp. *laidlawiana, Lasiopetalum floribundum, Clematis pubescens, Macrozamia riedlei, Leucopogon capitellatus, Leucopogon verticillatus, Phyllanthus calycinus* and *Pteridium esculentum*, corresponding to Strelein's site types Q, U and V. In the driest variant in the semiarid-arid zone (WH 3) the slopes of the landform support a woodland of wandoo and marri, largely without a second storey and with an understorey of *Macrozamia riedlei, Hibbertia commutata, Hakea lissocarpha, Leucopogon propinquus, Leucopogon capitellatus* and *Trymalium ledifolium*, corresponding to +C1 and +C2 of Christensen's (1980) ordination.

At the level of the vegetation complex, an effort was made to reduce or eliminate the effect of climate, which operates on the widest scale. As described in the previous section, the strategy employed was to subdivide the landforms that were geographically most extensive, into subsets which were as far as possible climatically homogeneous in terms of the annual rainfall/summer evaporation criteria. By doing this the first stage of correlation between factors of the environment and the vegetation was reduced to correlation between vegetation and landform. This was based on the assumption that in the southwestern region, where plateau landscapes are prevalent, there is a high degree of integration between topography and soils. By this is meant that in the plateau landscapes, fertile soils are generally confined to areas of strong dissection, in which the old leached and infertile soils such as the lateritic gravels and sands have been removed by erosion. These are then replaced by relatively young soils formed directly on the parent material during a more recent cycle of weathering and soil formation. The primary assumption that was either implicit or explicit in the landform maps that were used as the basis for the mapping of vegetation.

The above assumption is particularly relevant to the crystalline plateaux but is slightly less relevant to sedimentary plateaux composed of materials that have already undergone one cycle of weathering and leaching. On the coastal plains, where the chief determinant is the nature of the materials re-deposited either by the rivers or the sea. There, the dissection tends to be subdued. Even under these conditions the time lapse is significant, in that the most recently deposited material is likely to be the least leached and hence the least infertile. In the case of coastal dunes, the very high calcium content of young dunes has adverse effect on the minor element availability.

The second assumption was that the sites with steep slopes would have above average drainage, both superficially and in the subsoil, so that the soil water storage and hence moisture availability during the summer drought would be the least. It was also assumed that on these sites soil aeration during their winter water surplus would never be limiting to plant growth. By contrast, level or concave sites would tend to have below average level of drainage, and may receive run-off from the neighbouring slopes, resulting in waterlogging or even flooding during the winter, with the accompanying inadequate aeration of the soil. This deficiency would then be compensated, at least to a degree, by better availability of moisture during the summer drought season.

Fieldwork – Pattern of Sampling; Data Recorded

The fieldwork consisted of the following stages:

a) Checking on field boundaries, particularly when landform maps by different authors had to be matched
b) Establishment of plots to ensure that each landform had some representation in terms of vegetation within the database
c) Description of toposequences representing various landform/climate combinations, particularly those not covered by earlier vegetation classifications.

The toposequences were constructed so as to record the range of variation in topography, soils and vegetation within a set of climate/landform combination. Wherever possible, this was done in a specific locality, but often information had to be obtained from more than one locality. Fore example, to describe the changes between plateau, upland landforms and neighbouring valley landforms, the extensive and relatively uniform upland landform had to be condensed into a fraction of its full extent. This means that the valleys shown on the toposequence as being separated by a plateau of 100-150 m width may be in fact separated by several hundreds or even thousands of metres.

Data Entry and Data Collation

A substantial amount of time in the vegetation project was spent of locating, enterring and updating (taxonomic nomeclature where feasible, although some names were not current and specimens could not be traced for some other authors).

The data merging was undertaken in conjunction with the vegetation mapping and the authors recognized that there were major gaps in the data sets as presented. The latter was summarized in the report by Mattiske Consulting Pty Ltd in 1996. To enable the vegetation map to be undertaken, the team at Mattiske Consulting Pty Ltd established over 1200 sites throughout the south west forest region in areas which had not been covered by previous authors. Even then the enormity of the survey area necessitated a reliance on reconnaissance work, particularly in areas where the vegetation had been extensively cleared or modified by agricultural activities. In these areas there was a need to rely on the underlying landform and soil maps (Smolinski 1999) to enable extrapolation from the remnant pockets to the wider mapping units.

The data was enterred onto an Access database established by Mattiske Consulting Pty Ltd. In many instances, the latter entailed requesting the original hard copies of data from prveious authors and previous listings from un-labled diskettes and listings. In part the latter reflected the 40 years of data collection. The merged data set provides a milestone in the State of Western Australia in terms of integrating a large range of authors work and databases. There were many constraints on the datasets as merged as the data was collected in different forms and from different sizes of sampling areas, however the data enabled substantial checking of the vegetation mapping units as defined by Mattiske and Havel for the vegetation complexes.

Definition of Relationship between Climate, Landform and Vegetation

The aim of this section is to define relationships between environmental factors, in particular climate and landform, and the vegetation, as the next step in defining mapping units that combine both abiotic and biotic components of the ecosystem. To a degree this has been already done in establishing the continuity between existing localised classifications, as such classifications are usually based on relationships between the vegetation and underlying environmental factors.

However, it is proposed to examine these in greater detail in this section. The effectiveness and reliability of the approach is determined by the degree of understanding that exists on the relationship between the gross environmental features such as landforms and climate and the finer features of the vegetation, in particular its floristic composition. The understanding has to cover the intermediate scale features such as soils and structure of the vegetation as well.

A plant community or vegetation type, defined by a set or sets of species (characteristic species, indicator species) is an implicit statement that a relationship exists between vegetation and the site on which it grows. There are numerous examples in the Australian ecological literature of studies of relationship between the vegetation and the underlying environmental factors (Le Brocque and Bickney 1994; Hahs *et al.* 1999; Busby 1986; Coates and Kirkpatrick 1992; Kirkpatrick *et al.* 1987; Burgman 1988; Froend *et al.* 1987; Davidson and Reid 1989; Brown 1989; Elliott *et al.* 1983; Enright *et al.* 1994). There are also some articles which deal specifically with the methodology of relating vegetation to the environment, in particular Austin *et al.* (1996) and Belbin (1992). Regrettably, the heterogenepis nature of the vegetation data available for the southern forests preclude the use of these more objective methods here. The discussion that follows is focussed on studies of the relationship of vegetation to environment within the Jarrah and Warren bioregions.

Early Qualitative Descriptions

Even though quantitative analyses were not feasible in the earliest vegetation studies, the conclusions reached by the early ecologists are generally still valid, and are considered here. Diels (1906) considered the jarrah forest to be delineated by the 750mm isohyet. This is only a rough approximation that ignores the effect of evapotranspiration, for which no data was available at the time. He recognised that edaphically favourable sites compensate for lower rainfall in the most easterly extension of the species. Jarrah was seen as being associated with gravelly uplands, but its extension on to the sandy coastal plain, with a corresponding reduction in structure from tall forest to woodland, was recognised. Among the outstanding features of the forest, is the purity of its overstorey, in that, apart from marri *(Corymbia calophylla*), no species enters into; the uniformity of the small-tree understorey, restricted to eucalypt regeneration and a few Proteaceous species; and the diversity of the shrubby ground vegetation, which contrasts so strongly with the floristic paucity of the tree strata.

In dealing with individual tree species, he associated marri (*Corymbia calophylla*) with moist, fertile sites, sheoak (*Allocasuarina fraseriana)* with sandy soils, *Banksia grandis* with gravelly uplands, *Melaleuca preissiana* and *Banksia littoralis* with swamps, and *Banksia attenuata* and *Banksia menziesii* with deep sands. Of the eastern species, wandoo (*Eucalyptus wandoo*) was considered to be restricted to heavy-textured soils underlain by clay, alternately wet in winter and dry in summer, and *Allocasuarina huegeliana* to granite outcrops. These were rather generalized conclusions, which could be readily made by anyone acquainted with the forest. Nevertheless, they were virtually overlooked in subsequent years. Even more remarkable was his perception of the distribution patterns of the smaller perennials. He associated the genera *Petrophile* and *Isopogon* with sandy gravels, *Gastrolobium* with dry gravels, and *Viminaria*, *Cladium* (syn. *Baumea*), *Boronia, Astartea* and *Agonis* with swamps. Of the families, he considered Epacridaceae to be most restricted by external conditions, but relatively poorly developed in the moister south; Myrtaceae to be bimodal, with strongest occurrence in swamps and sands; Restionaceae to be largely restricted to swamps; and Orchidaceae to be controlled more by fire than by edaphic conditions.

Another of his remarkable perceptions was the recognition of a north-south trend in species distribution, as well as the more obvious east-west one. He considered that the optimum of the jarrah forest occurred in the middle Blackwood Valley. *Acacia nigricans, Hypocalymma cordifolium, Pteridium esculentum* (formerly *Pteridium aquilinum*), *Adiantum aethiopicum* and *Trymalium floribudumu* (formerly *Trymalium billarderii)* were listed as the under-growth associates of jarrah on optimum sites.

Williams (1932, 1945) concluded that plant communities were indicative of soil conditions, but that individual tree species, and in particular individual shrub species, were of limited value for this purpose. He found that the species complex of the lateritic uplands differed markedly from the species complex of the dissected landscape and soils derived from fresh-rock exposures. Within the latter group he found species with preferences for soils derived from granite and epidiorite respectively. Yet another set of species was associated with the moist alluvium. A number of species failed to show any edaphic preferences.

Marri was considered by Holland (1953) to be more flexible in its habitat requirements than jarrah, which was considered to be incapable of competing on good soils and to have a narrow tolerance to moisture fluctuations.

The 500 mm isohyet was considered by Lange (1960) as being the most significant climatic criterion, dividing the coastal high rainfall tree species from the inland low rainfall ones. Whenever the western species occur east of the dividing line, it is invariably as outliers on deep lateritic soils or on sandy soils in moisture-gaining depressions. He attributed the disjunct occurrence of the western species to an arid period in the late Quaternary, as postulated by Crocker (1959). The overall effect of increased aridity was the contraction of these species to favourable sites.

The vegetation of south western Australia, within which the Jarrah and Warren bioregions are located, was considered by Churchill (1961,1968) to be a continuum primarily determined by rainfall, in which each species occupied a distinct segment. To illustrate this, he provided distribution maps of many tree, shrub and perennial herb species. Havel (1975a) examined these distribution maps for communality of distribution and identified 16 groups of species, which had a shared distribution pattern. These are described in Appendix 3.1. Churchill (1961,1968) considered the balance between the major forest components (*Eucalyptus marginata, Eucalyptus diversicolor* and *Corymbia calophylla*) to be determined by the rainfall of the wettest and the driest months of the year, indicating that water availability was a major influence. He considered these species to have very wide edaphic tolerances within the high rainfall belt. By contrast, no such relationship with temperature data was found. The three species discussed appear to have very wide edaphic tolerances within the high-rainfall belt.

Finally, in relating the vegetation types to edaphic and geologic units Griffin (1992) found that vegetation was more influenced by geological substrate than by surface soils. There was also a strong relationship with topography, in particular as it reflected the stripping of the plateau by erosion.

Principal Component Analysis and Regressions

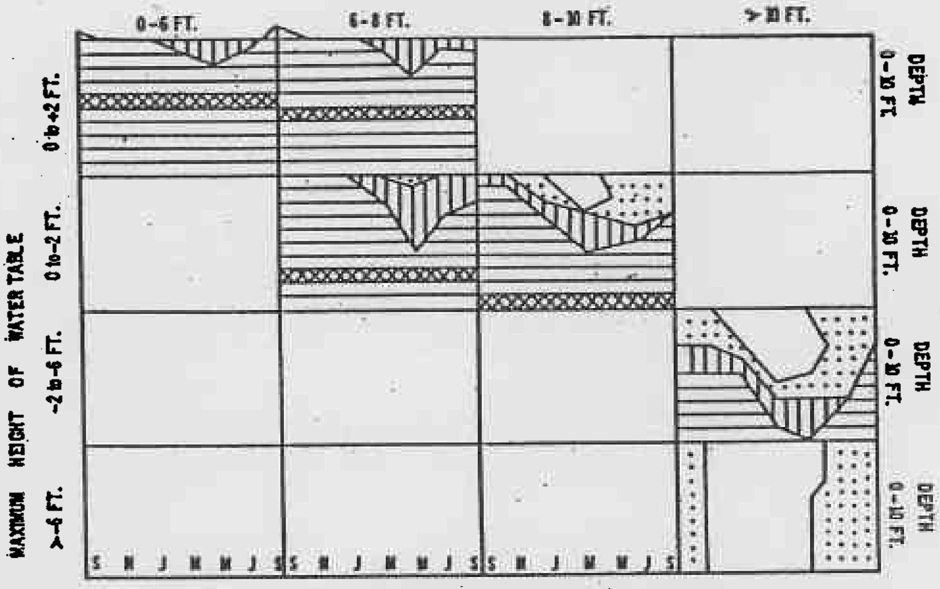
The establishment of relationships between vegetation and soils was the principal objective of Havel's (1968) studies of the northern Swan Coastal Plain. He utilised the principal component analysis of Goodall (1954,1963) as the primary tool for this. A consistent progression was established from the plots with the highest percentage of iron, and hence the least leached, to those with the lowest percentage of iron and hence the most leached. The second most important environmental factor that emerged was of moisture availability. By inputting the frequency data of individual species in the plots into the principal component framework, it was possible to assess their value as indicators of the soil parameters. These relationships between vegetation and environmental factors are illustrated in Figure xx (3.1) and xx (3.3).

This relationship was expanded to more extreme sites, not covered by his initial sampling, by combination of permanent transects and Pogrebnyak's (1955) edaphic net. The edaphic net covering the deep leached sands of the Bassendean Dune System identified a dynamic rather than static parameter, that is annual fluctuations of the groundwater table and moisture availability, as the chief determinant of vegetation patterns [redacted] Subsequent observations over 33 years (1956 - 1999) have shown that even this parameter is subject to year-to-year fluctuations. When these combine into a trend, such as that caused by a sequence years of below-average annual rainfall, there is a corresponding shift in the vegetation continuum (Heddle 1980; Mattiske Consulting Pty Ltd 1995).

In the northern jarrah forest, Havel (1975a,b) attempted to relate vegetation patterns to the underlying environmental factors through a number of different approaches. The most quantitative of these was by means of stepwise multiple regression of plot scores derived by principal component analysis of floristic data against observed environmental parameters, for 171 plots from the northern sector of the jarrah forest. The full description of this is given in Appendix 1.1, the shorter summary of the relationships is given in Appendix 3.2. An example of the integration of the vegetation and the environment is described below and illustrated. On the basis of this, the first component (F1) was found to be most closely related to maximum slope ($r = +0.536$) and percentage gravel in topsoil ($r = +0.390$). +F1, also is associated with site-vegetation types T and U. These types thus occur in the highly dissected western zone of the jarrah forest, on gravely loams and loamy gravels, and are defined by three indicator groups: HIGRA (high rainfall gravels) which consists of *Leucopogon verticillatus, Pteridium esculentum, Clematis pubescens;* FREGRA (fresh gravels) which consists of *Macrozamia riedlei, Leucopogon capitellatus, Leucopogon propinquus* and *Phyllanthus calycinus;* and GRAHIR (gravels, high rainfall) which consists of *Acacia urophylla, Lasiopetalum floribundum* and *Bossiaea aquifolium*. Weaker correlations were found between the first component and cation exchange capacity of the soil (CEC), percentage saturation of the CEC and levels of calcium, phosphorus and potassium. The average percentage saturation of the CEC was 70 for type T and 82 for U, which is well above average for the forest as a whole. The average calcium level [ex Ca (me%)] was 7.3 for T and 13.1 for U, again well above average for the forest as a whole. The multiple regression co-efficient for combined maximum slope, percentage gravel in topsoil, percentage saturation of the CEC and level of calcium in the soil was 0.633. The equivalent process for components F2, F3 and F4 is given in Figure 3.4

WATER REGIME SEPT. 1965 - SEPT. 1966

DEPTH TO DEPOSITION HORIZON



RELATIVE BASAL AREA (PERCENT) OF TREE SPECIES

B. ATTENUATA

1.4	11.4		
	13.1	21.7	
			55.1
			44.8

B. LITTORALIS

1.7	1.7		
	0.3		

B. MENZIESII

	2.8	5.6	
			10.3
			42.8

B. ILICIFOLIA

1.7	6.0		
	12.6	44.5	
			30.0
			1.7

E. CALOPHYLLA

	8.9	1.2	

E. MARGINATA

	46.0	4.8	

E. TODTIANA

	1.0	0.9	
			1.1
			6.7

MELALEUCA PREISSII

81.8	63.5		
	13.7	17.5	

NUYTSIA FLORIBUNDA

8.7	0.5		
	2.9	3.4	
			2.1
			3.0

NON-SPECIFIC FEATURES OF TREE STRATUM.

TOTAL BASAL AREA (SQ. FT./ACRE)

61.9	50.2		
	86.6	45.5	
			47.8
			27.2

MAXIMUM HEIGHT (FT)

35	42		
	49	38	
			31
			24

LEGEND: SOIL MOISTURE LEVELS

M.C. <3% M.C. 3-10% M.C. 10-20% M.C. > 20% DEPOSITION HOR.

Total phosphorus (P) p.p.m. in top soil

55	31				+ F4 + 8.2
60	28	15	18	14	
102					
118					
232					- F4 - 23.0

- F2 + F2

- 5.3 + 26.0

Figure 3.4 **Patterns of environmental parameters within component space calculated on the basis of vegetational data. The values plotted are the mean values for sample plots falling into the particular segments of component space. (Second approximation, varimax scores, 55 shrub and tree species.)**

Havel (1975a) also related site parameters to one another and found a high correlation between parameters reflecting site fertility, and between these and pH, percentage of silt and clay, field capacity and available moisture. All of these were highly significantly correlated with maximum slope, presumably because of the strong geomorphological control over soil formation, namely that only where the lateritic or silicious overburden has been stripped by erosion could fresh loamy soils with high fertility and moisture retention be found.

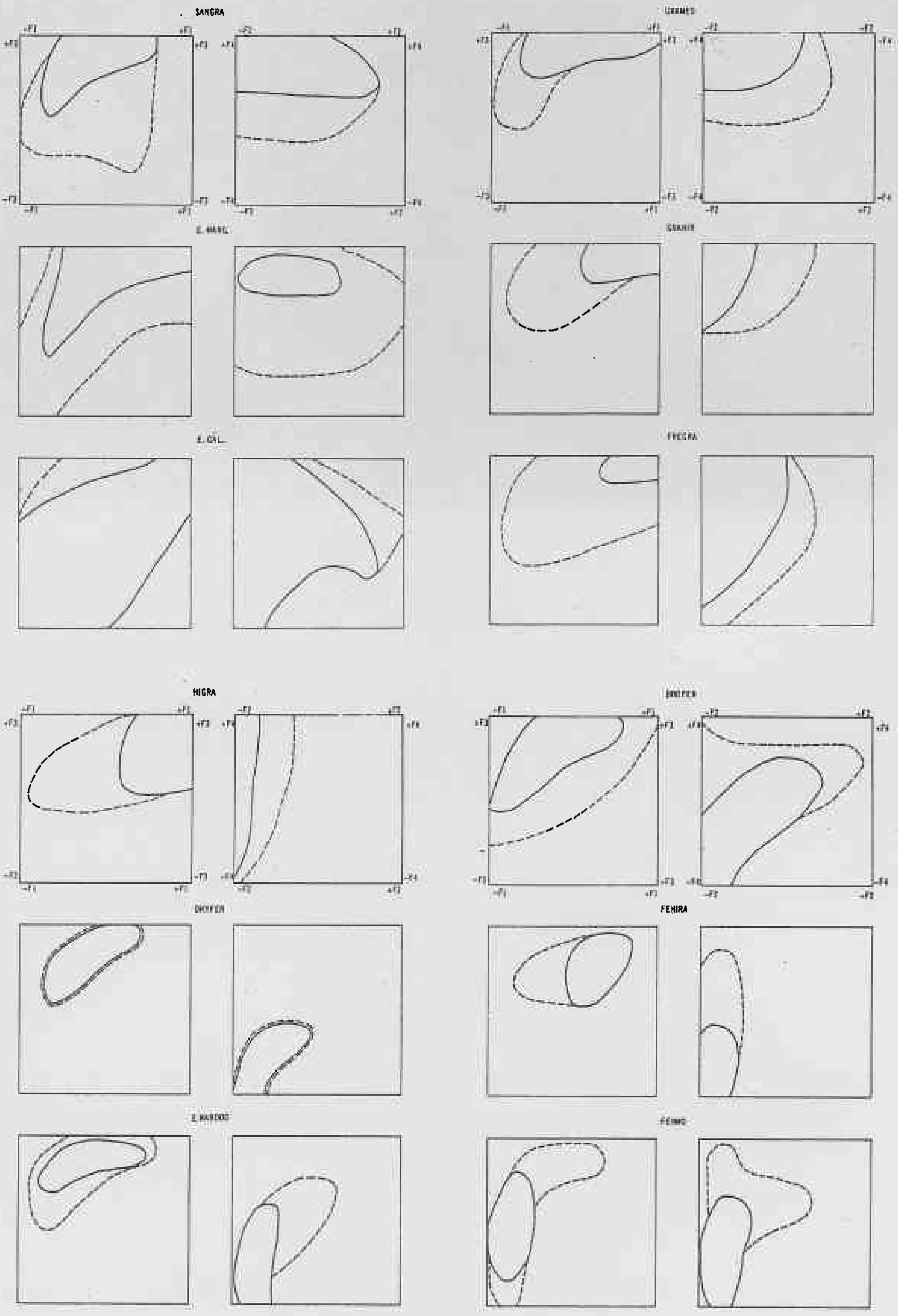
He summarised the correlations between component scores derived from vegetational parameters and directly measured environmental parameters as follows:

a) The component scores cannot be simply expressed in terms of individual environmental parameters.

b) Environmental parameters explain only a portion of the total variation in component scores. In view of the fact that only a portion of the environmental complex (some aspects of topography and some physical and chemical factors of the topsoil) could be quantified, this too can be expected.

To facilitate the examination of the relationships between the plots, of their physical properties and of the vegetation within them, a special display program (CORD) consisting of a 20 x 20 matrix for any combination of two principal components was developed. Within this matrix the plots were plotted according to their scores on the relevant components, and attributes of the plots were then displayed. This made it possible to relate the principal component axes to environmental variables and to patterns of species distribution, and ultimately to subdivide the four-dimensional continuum into groups of species with similar physical and biological attributes. The distribution of some of the species groups in the component space is shown in Figure 3.22.

APPENDIX 3.22:



It was only a substitution of a hybrid mathematical/graphical approach for a purely mathematical one, so that the relationships described earlier held good. However, the approach made it easier to relate the environmental parameters to more than one principal component at a time. For instance, the component space delineated by - F2 and -F4 was characterised by high levels of phosphorus, potassium, calcium and magnesium, by high cation exchange capacity, by high field capacity and high wilting point (Figure 3.4). By contrast the component space delineated by high –F1 and –F3 was characterised by acid soils with the lowest phosphorus, potassium, calcium and magnesium levels, high exchangeable hydrogen, mild slopes and absence of gravel. Whist in many environmental parameters the combinations –F1 x -F3 and -F2 x -F4 appeared to be diametrically opposed, this was not true of all parameters. It can, however, be assumed that these two combinations do provide two extremes of the environmental continuum, namely the fresh, well drained and fertile loams on the slopes of the major valleys and the leached, impoverished sands in mildly sloping, poorly drained depressions in the headwaters of rivers. Havel (1975a) concluded that both the mathematical and graphical approaches pointed to a highly interrelated environment/vegetation complex that defied simplification.

Principal component analysis (PCA) was used by Loneragan (1978) as the most convenient method of dealing with the environmental (site) data. This elucidated the relationship between the site descriptors, namely that they formed a continuum. It indicated that in the studies of Loneragan most sites in the high (over 750 mm annual rainfall) were on the gravel deposits of the mildly sloping stable surface of the old plateau and had coarse texture. By contrast, most of the sites below the 625 mm annual rainfall had soils of finer texture and higher level of nutrients, indicating greater dissection of the lateritic plateau, described as an erosional surface. Most of the latter sites presumably occurred on the dissection caused by eastward flowing tributaries of the Avon River. The coarsest textured soils of more that 70% of coarse sand, were found on sites described as depositional.

Loneragan also related the principal component axes of the tree analysis to environmental data by means of regressions and obtained significant correlations, both to raw environmental data and to component scores of the PCA based on them. The strongest correlations were those between the PCA scores on trees and rainfall and silt and clay fraction. The correlations with soil chemical attributes such as N, P and K were weaker.

The chief factors determining the vegetation patterns on the Blackwood Plateau were considered by McCutcheon (1978,1980) to be the presence of lateritic horizons in the subsoil, the texture of the soil and soil moisture conditions as determined by soil characteristic and topographical position. The level of soil fertility, which is almost universally low in this region of lateritised and reworked sediments, found expression through the texture of the soil, the heavier textured soils having better nutrient retention capability and hence being more fertile than the deep leached sands. Quite strong correlations were found between the vegetational gradients and the soil parameters. The vegetation types typical of deep leached sands, moist fine textured loams of the valley floors and the poorly drained soils of intermediate texture could be defined on the basis of vegetation alone. The less leached sands, and in particular soils with gravelly horizons within them, required probing, as the vegetation was not seen as being sufficiently precise in defining the effective depth of soil.

Strelein (1988) used the output of the principal component analysis of the southern jarrah forest to interpret the interspecific relationships and to assess the underlying factors. The second stage of the output, namely component scores for the plots, was used to construct a four dimensional model showing the position of the plots within the component space. To facilitate interpretation, the component scores were also used to develop a set of two dimensional diagrams by means of the CORD ordination program, in which any of the plot attributes could be displayed. The plot parameters examined were soil and site data as well as the individual species present on the plots.

Strelein (1988) related his types to factors of the environment both verbally and by means of diagrams. In his descriptions of the principal components he referred to the first component as reflecting both fertility and texture, the extremes being fertile loamy soils at -C1 (high carbon, high nitrogen, high phosphate and high potassium) and infertile gravel soils at +C1 (low carbon, low nitrogen, low phosphate and low potassium). The combination of fertility and texture reflects the fact that the lateritic gravels of the plateau uplands have been through a cycle of acute leaching, leaving them chronically deficient in phosphate and potassium, whereas the loamier soils of the valley slopes are continually being renewed by erosion and breakdown of the granitic or dioritic country rock. A fuller description of the relationship identified by Strelein is given in [redacted]

On the whole, Strelein (1988) detected similar basic relationships between vegetation and the underlying environmental factors in the moister southern jarrah forest as Havel (1975a,b) did in the drier northern jarrah forest. There was, however, a significant shift that reflected the climatic differences between the two.

Test Surveys, Computer-based Map Overlays and Chi-square Test

Having defined site-vegetation types in the northern jarrah forest by principal component analysis and ancillary programs, Havel (1975a, b) set out to test whether the categories defined were more than mathematical abstractions without a counterpart in the real world. In order to test this, and to relate the site-vegetation types to landscape and climate, mapping was undertaken on a number of test areas spanning the range of climatic and geomorphological variation in the northern jarrah forest from west to east. The areas mapped were mostly catchments of tributaries of the Canning River, which traverses the region from east to west, except for the easternmost one which was situated on the headwaters of a tributary of the Dale River. Those on the Canning River reflected the deepening dissection of the landscape as the river flows from the divide with the Dale River towards the coastal plain. The test areas ranged in size from 1823 to 2789 ha, and totalled 8783 ha.

The objectives of the surveys were:

a) the existence of the site-vegetation types in real space,
b) the reliability of predictions about relationships between the plants and the environment,
c) the feasibility of mapping the types rapidly, with the use of aerial photographs, and
d) the feasibility of inferring vegetation from geomorphology and climate.

The surveys were carried out along traverses across the grain of the country, to maximise the information collected. In the initial survey of a strongly dissected catchment close to the headquarters, the traverses were 400 m apart and observations were made at 100 m intervals. For the more distant and generally less dissected catchments this was increased to 800 m x 200 m. At each observation point standardised observations were made on environmental parameters such as topography, rock outcrops, soil texture and condition of the forest in terms of height, basal area, logging impact and disease occurrence, and on the occurrence of plant indicators defined by the earlier study. The data thus collected was transferred to standard forestry maps at the scale of 1:15840, and the maps encoded for use with the MIADS (Map Information and Display System) of Amidon (1964,1966), adjusted for local use. The map data was entered by means of a numerical code for cells 4 mm x 5 mm, equivalent to 0.54 ha on the metric scale. The MIADS system made it possible to overlay maps and assess the degree of covariance or coincidence between the various mapped attributes, by combining two encoded maps and producing a combination map and a set of tables giving the area and the proportion of the total area falling into each combined category.

A program (CONTAB) was developed locally to convert the output for MIADS into multidimensional contingency tables and to subject these to Chi-square test for goodness of fit (Fienberg 1970). The full study cannot be reported here, but is contained in Appendix 1.2. A specific example is presented here which involves the site-vegetation types described earlier. The westernmost test area surveyed (Ashendon) was largely a catchment of a minor tributary of the Canning River, in which high rainfall (1200-1350 mm/year) was combined with strong dissection of the plateau because of proximity to the Darling Scarp. A brief resume of the relationships, and the conclusions reached, are described in [redacted]

The site-vegetation recorded in this test area were C, D, W, Q, R, T, S and P. ([redacted] The T vegetation type, an open forest of *Eucalyptus marginata* subsp *marginata* – *Corymbia calophylla* with minor admixture of *Eucalyptus patens*, was found at 4.4 times above the expected occurrence (assuming random distribution) below 213 m, at 4.7 times between 213 and 244 m, at 2.2 times between 244 and 274 m and at below the expected occurrence above 274 m. The ratio of observed to expected occurrence in relation to slope was 2.6 for slopes of more than 8°, which in local context is steep, and below 1.0 for plateaus, depressions and mild slopes of less than 8°. The ratio in relation to soil texture was 0.2 for sand, 0.3 for gravelly sand, 0.6 for sandy loam, 0.7 for sandy gravel, 1.8 for silty loam and 3.4 for loamy gravel. This translates to occurrence on steep slopes below the main level of the plateau, on loamy gravels and loams. The remainder of the vegetation types of the Ashendon Test Area, are covered in [redacted]

The Leona test area was a catchment of a minor headwater tributary of the Canning River that reached to the Canning-Dale divide, in which low rainfall (750-875 mm/year) was combined with mild dissection of the plateau because of the distance from the Darling Scarp. The site-vegetation types recorded in this test area were A, E, J, H, L, M, P, S and Z. Types Q and T were totally absent and S was restricted to the wetter western margin of the catchment. The detailed description of the relationships is contained in [redacted]

On the basis of these tests it was established that the site-vegetation types exist in real space. Two of the types established by the ordination process (U, F) were not located on a mappable scale on any of the test areas, though they have been located in other areas subsequently. Two types were found to be too broadly defined and were subdivided by reference to related types, e.g. AY, with some characteristics of both type A and type Y, and JH and HM, differing in soil texture. A whole new complex of types, from woodlands to herbfields, with pattern too fine to be separated into mappable homogeneous types at the scale of 1:10,000, was found on the rocky slopes of the Cooke monadnock and was defined as a new category G.

It was also confirmed that site-vegetation relationships identified by the principal component analysis exist in real space, eg that site-vegetation A is invariably found on water-gaining sites and types T and S on uplands, type J on sandy soils and type Q and T on loamy soils, types S and H predominantly on plateau uplands and Q in dissected valleys, types Q and T in high rainfall and H and J in low rainfall.

The information summarised above is only a fraction of the total information pool in Havel (1975a,b). It also presents a simplified picture, in that the site-vegetation types discussed were those at the extremes of the principal component framework.

Havel (1975b) summarised the survey information in the form of cross-country transects, which are near-equivalent of Canadian toposequences. These show, in profile, the shape of the landforms and the distribution of the tree species, site-vegetation complexes and soil-texture classes. This facilitates understanding of the relationships between the various components of the landscape.

As a final summary of the trends he concluded that " *in the Darling Range one encounters the unique situation in which a strong geomorphological trend, largely controlled by distance from the escarpment, is overlain by an equally strong, parallel climatic trend also conditioned by distance from the escarpment. This reinforces the integration already described on a local scale, and leads to further simplification of vegetational patterns. There are, however, several exceptions to this, and these provide valuable reference points by which the effect of the integration can be measured.* "

It was also found that only extreme sites, such as rocky slopes and swamps, on which the height and density of the tree stratum were significantly reduced, could be mapped on the basis of aerial photography. For bulk of the types the stand features visible on aerial photos were not sufficiently distinct.

However, it was also found that there was a strong relationship between site-vegetation types and geomorphic surfaces. Each combination of a geomorphic surface and climatic zone was associated with a set of site-vegetation types, generally arranged in topographic continuum, such as from a water-shedding ridge to water-gaining lower slopes and valley floor. As the geomorphic surfaces could be mapped from aerial photos, they provided the means for preliminary mapping of large areas for land use planning on an ecological basis. The precision of this mapping could be subsequently improved by ground surveys.

The mapping of the extensive areas of forest made it possible to examine the factors controlling the occurrence of the tree species within the region, the chief of which was found to be the availability of water. This, in turn, was determined on broad scale by climate and on local scale by topographical position and the depth of the soil profile accessible to tree roots. It was this that determined the dominance of jarrah on the deeply weathered lateritic uplands over a wide range of climatic zones, and its displacement by more drought tolerant species on truncated soils of the valley slopes, especially in lower rainfall of the east and north.

Bettenay *et al.* (1980) linked together the hydrology, pedology and plant ecology of a set of minor catchments in the south of the Jarrah bioregion. They defined four hydrologic provinces in each catchment, ranging from the slopes adjacent to the streamline which contributed to the stream flow, to the upper slopes and divides on which the incoming rainfall was fully absorbed into the highly permeable soil. A resume of this important study is contained in Appendix 3.5.

Heddle (1979) and Heddle *et al.* (1980) extended the interpretation of vegetation patterns in relation to landforms and climate into vegetation complex mapping for the Darling System (System 6 mapping). This area covers approximately a third of the South-West Forest Region. In the development of this mapping technique Heddle *et al.* (1980) relied on the previous studies in the area and in particular the detailed site-vegetation type work of Havel (1975a,b), the Aerial Photographic Interpretation (API) mapping by the Forests Department of Western Australia, the topographic data held by the Department of Land Administration, the landform and soil mapping of Churchward and McArthur (1980) and, the previous vegetation mapping by Smith (1974) for the Collie area. It was similar to the land system approach of Christian and Stewart (1953) used in the Katherine - Darwin region. The studies by Beard (1979a,1979b) were being developed concurrently with those of Heddle *et al.* (1980) and therefore the essentially structural formation mapping of Beard was not available to Heddle *et al.* (1980) at the time of the mapping.

The definition of the vegetation complexes in terms of floristics is given in [redacted]

Mapping Unit No.	Vegetation Complexes	A	B	C	D	E	F	G	H	J	L	M	O	P	Q	R	S	T	U	W	Y	Z
1	Dwellingup-Hester												+	+		+	*	*				
2	Dwellingup								+				+	*		+	*					+
3	Dwellingup-Yalanbee							+	*					*		+						*
4	Dwellingup-Yalanbee-Hester								*					+								*
5	Yalanbee-Dwellingup							+	*			*										*
6	Yalanbee							+	+			*										+
7	Cooke							*				+				*	+					+
8	Goonaping	+	+				*			*												
9	Wilga					+			*							*				*		
10	Yarragil (Min. Swamps)			*	*										+			+	+	*		
11	Yarragil (Max. Swamps)	+	+		*	*	+			+				+						*		
12	Swamp	*																				
13	Pindalup-Yarragil	+				+			*		+	*									*	+
14	Coolakin							+	+		+	*									*	+
15	Catterick			*	*										*					*		
17	Helena			+				*							+	*		+				
18	Helena			+				*							+	*					+	
19	Bridgetown			*				+							*	+		*	+			
20	Murray			*	+								+		*	+		*	*	+		
21	Murray-Bindoon	+		+				*	+		+	+			+	*				+	*	
22	Balingup			*	*												+	+		*		
28	Darling Scarp							*								*						

Legend:

- * Site-Vegetation type should be present.
- + Site-Vegetation type should be present, but absence not critical.

The definition of the vegetation complexes in terms of structure is given in Table 3.

Table 3

Mapping Unit No.	Vegetation Complexes	TALL OPEN FOREST	*E. diversicolor*	*E. marginata-C. calophylla*	OPEN-FOREST	*E. marginata-C. calophylla*	*E. marginata-C. calophylla-E. patens*	WOODLAND	*E. wandoo-C. calophylla*	*E. wandoo*	*E. wandoo-E. accedens*	*E. loxophleba*	*E. rudis-M. rhaphiophylla*	OPEN-WOODLAND	*E. wandoo*	LOW OPEN-FOREST	*A. huegeliana*	*M. preissiana*	*C. obesa*	*Agonis flexuosa*	*E. rudis-M. rhaphiophylla*	LOW OPEN-WOODLAND	*E. wandoo-C. calophylla*	*B. attenuata-B. menziesii*	*M. preissiana-B. littoralis*	OPEN-SCRUB	*C. obesa-Acacia spp.-Melaleuca spp.*	HEATH	Closed	Open
1	Dwellingup-Hester																	+	+		+		*	*						
2	Dwellingup											+						+	*		+		*							+
3	Dwellingup-Yalanbee										+	*							*		+									*
4	Dwellingup-Yalanbee-Hester											*							+											*
5	Yalanbee-Dwellingup										+	*					*													*
6	Yalanbee										+	+					*													+
7	Cooke										*						+		+		*		+							+
8	Goonaping		+	+						*			*																	
9	Wilga								+			*									*						*			
10	Yarragil (Min. Swamps)					*	*													+				+	+		*			
11	Yarragil (Max. Swamps)		+	+			*		*	+			+						+								*			
12	Swamp		*																											
13	Pindalup-Yarragil		+						+			*			+		*												*	+
14	Coolakin										+	+			+		*												*	+
15	Catterick					*	*													*							*			
17	Helena					+					*									+	*			+						
18	Helena					+					*									+	*								+	
19	Bridgetown					*					+									*	+			*	+					
20	Murray					*	+											+		*	+			*	*		+			
21	Murray-Bindoon		+			+					*	+			+		+			+	*						+		*	
22	Balingup					*	*																+	+			*			
28	Darling Scarp										*										*									

Legend:

* Site-Vegetation type should be present.

\+ Site-Vegetation type should be present, but absence not critical.

Havel Land Consultants (1987) surveyed four river basins in the northern jarrah forest by means of cross-contour (across valley) surveys. The basin studied covered quite a wide climatic range as well as considerable geological variation. The northern most of the river basin study (Mundaring) combined low rainfall with strong development of non-granitic basement rocks especially migmatite, as well as steeper than usual slopes. Consequently the dominant vegetation types were those containing wandoo woodlands Y, L and M and shrublands of type G. There was an abnormally high development of plant indicators of fertile sites. The lower Canning basin and the North Dandalup basins contained vegetation of more normal type, that is, developed mostly on granitic basement rock with only moderate degree of dissection. The types encountered were correspondingly of the more common types (W, C, T, Q, P) though there was still a considerable development of types G and R. The upper Canning basin (south Canning) consisted primarily of very broad mildly sloping valleys with extensive flat floors that were poorly drained. The dominant types in this catchment were therefore types A, C, W and Y. An example of the cross-valley transect is shown in Figure 3.6.

The environmental impact assessment for the Boddington Goldmine (Worsley Alumina 1999) resulted in the production of a detailed vegetation map. This gave the opportunity to relate vegetation patterns in relation to landform.

There was a strong relationship between vegetation types and land forms, of the woodlands of wandoo (Y, AY) yarri (*Eucalyptus patens*) (L) and WA flooded gum (*Eucalyptus rudis*) (AX) being mainly confined to the Pindalup (Pn) and Swamp (S) complexes and optimum development of the jarrah (*Eucalyptus marginata*) forest and woodland occurring on the Dwellingup (D3, D4) complexes. The Melaleuca shrubland type (A) was confined to the Swamp (S) complex. The heath complexes (G3, G4) were, however, not confined to the Cooke complex, but also occurred in small patches at interface between Pindalup and Dwellingup complexes. The maximum occurrence of the ST type, normally associated with high rainfall and high fertility, was on the Cooke complex along the western boundary, where ultrabasic parent material and additional orogenic rain presumably provide optimum conditions.

UPMGA Analysis and Ordination

In his study of the karri (*Eucalyptus diversicolor*) forest Inion's (1990a,b), used separate classifications of edaphic and climatic attributes to define 5 soil groups and 8 homoclimes respectively.

The soil groups ranged from relatively infertile acidic soils to the least acid soils with high fertility. The homoclimes ranged from coastal sites with high rainfall, low temperature and low radiation to inland sites with medium to low rainfall and higher summer temperatures, resulting in an overall drier climate. The climatic factors appeared to have a clearer effect on the performance of karri than the edaphic factors, bearing in mind that by restricting the sampling to regenerated karri stands the edaphically more favourable sites would have been selected. The less favourable sites in the region, carrying jarrah, were covered by Streleins's (1988) study.

Inions *et al.* also defined five community groups and subdivided these into thirteen community types. Relationships were sought between community types and environmental variables by ordinating the community types on the basis of precipitation in the driest quarter, radiation in the driest quarter and phosphate content of the soil, Figure 3.7. The extremes of the three-dimensional continuum were the Harris type of the leached soils in the cool and wet climate of the south coast, and the McNamara type occurring on more fertile soils in drier and hotter inland margin in the north of the species' distribution.

Inions *et al.* provided a set of indicator species which covered the continuum. The vegetation/site relationships described by Inions *et al.* include the following linkages:

> Marginal sandy acidic sites with low HCl extractable phosphate (25.2 +/ 3.1 ppm) – *Boronia gracilipes, Macrozamia riedlei, Persoonia longifolia* and *Podocarpus drouynianus* (Ednie-Brown community type)
>
> Gravelly yellow or brown duplex soils with moderately high HCl extractable phosphate (51.7 +/- 16.8 ppm) – *Chorizema ilicifolium, Lasiopetalum floribundum, Pteridium esculentum* and *Macrozamia riedlei* (Kessel community type)

Cold, wet, acidic sites with fairly low HCl extractable phosphate (37.5 +/_ 4.6 ppm) – *Acacia pentadenia, Allocasuarina decussata, Hibbertia furfuracea* and *Lepidosperma effusum* (Harris community type)

Warm, moist sites with moderately high HCl extractable phosphate (50.9 +/- 6.7 ppm) - *Hibbertia grossulariifolia, Callistachys (formerly Oxylobium) lanceolatum* and *Pteridium esculentum* (White community type)

Warm, seasonally dry sites with moderately high HCl extractable phosphate (54.6 +/- 4.0 ppm) – *Acacia urophylla, Hardenbergia comptoniana, Hibbertia amplecicaulis, Leucopogon verticillatus* and *Logania vaginalis* (McNamara community type)

Overall, Inions *et al.* considered water availability during the dry season, degree of inundation during the wet season, minimum temperature and soil phosphate to be the chief determinants of floristic patterns.

Relationships were sought between community types and environmental variables by ordinating the community types on original environmental parameters. The types were ordinated in three-dimensional space on the basis of precipitation in the driest quarter, radiation in the driest quarter and phosphate content of the soil, [redacted]. The parameters used in the ordination are probably the most significant environmental constraints in the region. The extremes of the three-dimensional continuum were the Harris type of the leached soils in the cool and wet climate of the south coast, and the McNamara type occurring on more fertile soils in drier and hotter inland margin in the north of the species' distribution. Inion *et al.* (1990a,b) also considered the ordination in component space defined from edaphic and climatic variables by Gower's (1971) principal co-ordinate analysis, but did not carry it out.

It is significant that although three dimensions were used in the ordination, there was a single overall continuum stretching between the Harris and McNamara types. Infertile sites (HCL extractable phosphorus in the A soil sample of less than 46.30 ppm) supported karri (*Eucalyptus diversicolor*) only in high summer rainfall (precipitation in driest quarter of more than 84.75mm) and low summer radiation (MJ m^2 day –1 of 79.92). By contrast, sites with low summer rainfall (less than 84.75mm) and high summer radiation (more than 79.92 MJ m^2 day –1) only carried karri if the sites were relatively fertile (HCL extractable phosphorus in A soil sample of more than 46.30 ppm).

This strong gradient in environmental variable was accompanied by a similar strong gradient in characteristic (indicator species), the extremes being Inions *et al.*'s groups HEATECO (heath ecotone) of *Acacia divergens, Dampiera hederacea, Hibbertia cuneiformis, H. furfuracea, Pimelia clavata, Scaevola microphylla* and SOBROSAN (southern broad sands) of *Agonis flexuosa* and *Anigozanthus flavidus* at the wet infertile end to Inions *et al.*'s groups NOREKA (north eastern karri) of *Amperea ericoides, Hardenbergia comptoniana, Helichrysum racemosum, Hibbertia amplexicaulis, Logania vaginalis, Orthrosanthus laxus* and *O. multiflorus* at the dry fertile end.

An intermediate species group at the moister end of the continuum is SOLOAM (southern loams) of *Chorilaena quercifolia, Eucalyptus guilfoleyi* and *Lepidosperma effusum.* At the dry fertile end the intermediate species groups is HIGRA (high rainfall gravels) of *Leucopogon verticillatus, Pteridium esculentum, Corymbia calophylla, Lomandra drummondii* and *Opercularia hispidula.*

A minor gradient also exists from infertile, wet and low radiation, represented by HEATECO, (already described above) to infertile, dry and high radiation, represented by GRAMED (gravels in medium rainfall) group of *Banksia grandis, Persoonia longifolia* and INFEKA (infertile karri) group of *Conospermum caeruleum, Hibbertia cunninghamii, Lomandra integra, Lomandra nigricans* and *Ricinocarpus glaucus*.

Wardell-Johnson *et al.* (1989) defined three broad groups, interpretable in terms of landform and drainage characteristic, namely poorly drained sites on granitic parent material or fluvial sediments, freely drained sites with good-moisture retention capabilities and sites on deep aeolian sands.

In the hill areas of the Walpole National Park there are sharp ecotones over short distances, and the soil components within the various landforms appear to be stronger determinants of the community types than the landforms themselves. Many of the soil types occur in more than one landform unit. In the swamps, the boundaries are more diffuse. The communities on the aeolian sands occur in a very complex pattern and have greater species richness.

In Gibson *et al.*'s (1994) study of the southern Swan Coastal Plain relationship was found between vegetation and landforms. At the level of the four supergroups, the grouping reflected major geomorphological elements, such as plains, swamps and young (Spearwood and Quindalup) and old (Bassendean) dunes.

Gibson *et al.* (1994) concluded that although floristic types are broadly correlated with geomorphological / geological units, there is not a direct one to one correspondence. Few community types are found on only one geomorphological unit, though some community types have relatively narrow geomorphological range. There is also negative correlation, in that some community types do not occur on certain geomorphological units.

In comparing the floristically based community groups with vegetation complexes of Heddle *et al.* (1980), Gibson *et al.* (1994) concluded that repeatable floristic communities, primarily determined by seasonal water regimes and geomorphology, do occur across the coastal plain, but groups of floristic communities are not restricted to particular vegetation complexes.

Qualitative Matching of Landform Maps and Vegetation Classifications

In this project Heddle *et al.*'s (1980) maps have been used, with minor modifications at the southern margin, as the basis for remapping the northern third of this project, the Jarrah Bioregion. As no studies comparable to those of Havel (1975b) have been carried out for the more diverse and complex Warren Bioregion it was necessary to examine alternative approaches to relating vegetation to landforms and climate. Fortunately, the mapping of Churchward and McArthur (1980) has been subsequently extended southwards (Churchward *et al.* 1988; Churchward 1992), and in contrast to the former study included considerable amount of botanical observation. In addition, the existence of these landform maps has enabled forest ecologists who carried out subsequent ecological studies in the Warren Bioregion (Strelein 1988; Wardell-Johnson *et al.* 1989,1995) to relate their observations of vegetation to landforms.

It is not possible to detail all the information utilised and all the analyses carried out to achieve this, but example will be given of the various sources and methods in view of the importance of this process for the Warren bioregion.

In the description of their mapping units (Churchward *et al.* 1988) included the following information:
BE (Bevan landform) - gently undulating surface made up of broad divides with short gentle slopes of less than 5° , extending into minor valleys, underlain by deeply weathered granitic rocks, largely without outcrops and including some unconsolidated sandy deposits

BEy is an edaphic variant, dominated by yellow duplex soils (Dy3.62) with greybrown sand to sandy loam surface incorporating ferrugineous gravel and some duricrust boulders, over a pale A2 horizon and weakly pedal clay B horizon.

BEy is described by them as supporting jarrah (*Eucalyptus marginata* subsp. *marginata*) and marri (*Corymbia calophylla*) tall open forest with an upper tree layer at about 30 m; a sparse small tree layer of *Banksia grandis* and *Persoonia longifolia*; shrub layer(1-2 m) of *Bossiaea linophylla, Bossiaea aquifolium* subsp. *laidlawiana, Xanthosia rotundifolia, Agonis parviceps, Opercularia hispidula, Synaphaea reticulata, Acacia obscura, A. myrtifolia, A. divergens, Hakea amplexicaulis* and *Hypocalymma robusta*; creepers *Clematis pubescens, Kennedia prostrata* and *Kennedia coccinea*.

In Strelein's (1988) description of vegetation types the following are considered to occur, partially or wholly, on landform BEy - S, T, V, Y and M.

Type S occurs on moderately dissected uplands in higher rainfall areas, with gravely duplex soils and much surface lateritic outcrops. Strelein described it as open forest with the following species as the primary indicators: *Banksia grandis, Persoonia longifolia,* (second storey) *Bossiaea linophylla, Boronia gracilipes, Gompholobium ovatum, Grevillea brevicuspis, Hakea amplexicaulis, Hovea chorizemifolia, Hovea elliptica, Leptomeria cunninghamii, Leucopogon verticillatus, Macrozamia riedlei, Petrophile diversifolia, Podocarpus drouynianus, Sphaerolobium medium* and *Xanthorrhoea gracilis* (shrub storey).

The less common associate species included *Acacia myrtifolia, Acacia pulchella, Agonis hypericifolia, Bossiaea aquifolium* subsp. *laidlawiana, Bossiaea ornata, Hakea lasianthoides, Isopogon sphaerocephalus, Lechenaultia biloba, Loxocarya flexuosa, Patersonia umbrosa, Pteridium esculentum* and *Xanthorrhoea preissii*. Strelein also referred to minor inclusion of moister sandy sites with *Adenanthos obovatus, Agonis parviceps, Kingia australis* and *Leucopogon concinnus*.

Type T differs slightly in soils, having less lateritic outcrops and yellow or reddish brown subsoil, indicative of higher fertility. It is mainly tall open forest of jarrah and marri;' *Clematis pubescens, Hakea amplexicaulis, Hovea elliptica, Leucopogon verticillatus, Macrozamia riedlei, Persoonia longifolia, Podocarpus drouynianus* and *Pteridium esculentum* are the primary indicators.

Type V was described as occurring on long sandy slopes that were less adequately drained than S and T and had brown or yellow sandy loams over brown or orange clay subsoil. It is an open forest whose primary indicator species are *Acacia extensa, Acacia pulchella, Acacia urophylla, Agonis flexuosa, Bossiaea linophylla and Clematic pubescens*, with *Leucopogon propinquus, Leucopogon verticillatus, Macrozamia riedlei* and *Persoonia longifolia* also present.

Type Y is described as coming from eastern broad flat drainage lines, with impeded drainage and dark grey clayey sand in upper profile. It is an open forest whose primary indicators are *Bossiaea linophylla, Bossiaea ornata, Hakea lissocarpha, Hypocalymma angustifolium, Leucopogon propinquus* and *Desmocladus* (formerly *Loxocarya*) *fasciculatus*. By comparison with S, T and V it has a lower rainfall and is less adequately drained, to the point of seasonal water logging. It is not strictly an integral part of the Bevan landform, but may occur within it as enclaves.

Type M is described as occurring on eastern slopes with brown sandy loams over gravely brown clays. It is a woodland or open forest in which the chief associate of jarrah is wandoo (*Eucalyptus wandoo*). The primary indicators are *Acacia pulchella, Hakea lissocarpha, Leucopogon propinquus* and *Trymalium ledifolium. Astroloma ciliatum, Astroloma pallidum, Macrozamia riedlei* and

Desmocladus (formerly *Loxocarya*) *fasciculatus* are also common. By comparison with types S, T and V this type has lower rainfall; by comparison with Y it is more fertile and better drained to the point of being droughty. It fits only marginally into the Bevan landform.

The comparison of the two approaches indicates that although geomorphologist put greater accent on the abiotic components of the ecosystem, and the ecologists on the biotic components, there is a broad agreement on the range of topographic and edaphic features and on the vegetation associated with them. The wider range of vegetation, which is strongly subject to climatic influences, indicated that geographically extensive landforms that extend over several climatic zones need to be subdivided.

In the case of the BEy landform it was found necessary to subdivide BEy into BEy1 and BEy2, and in the extreme case on the eastern periphery of the bioregion, to add BE3. Strelein's types S, T and V would mainly occupy BEy1 and to a lesser degree BEy2, types Y and M would occupy BEy 2 and type M would mainly occur on BE3.

By comparison with the upland landforms such as the one described above, the valley landforms tend to be more diverse in terms of both soils and vegetation.

Churchwood's (1992) Warren landform is described as valleys that are 60-100 m deep and 0.75 to I km wide, having slopes that range from 5° to 20° and floors that sometimes have a narrow terrace. There are few gneissic outcrops and the slopes are usually smooth and partially covered by colluvium. The dominant soils are red earths, though there are some yellow earths and red and yellow duplex soils on slopes and brown sandy loams on terraces.

Churchward describes the vegetation as tall open forest dominated by karri (*Eucalyptus diversicolor*), with marri (*Corymbia calophylla*) becoming more prominent with northward decrease in rainfall. The low tree layer is mainly *Banksia grandis, Agonis flexuosa* and *Allocasuarina decussata*. There is also a tall dense shrub layer of *Acacia pentadenia, Bossiaea linophylla, Hovea elliptica, Clematis pubescens* and *Chorizema ilicifolium*.

The valleys in this subregion are covered by Inions *et al.*'s (1990b) classification of the karri forest, more specifically his community types Shea, Stewart, Beggs, McNamara, Havel and White. Inions *et al.* does not specifically refer to landforms, as his study preceded the landform mapping of Churchward (1992) which covers the prime occurrence of karri. The Stewart and McNamara community represent the drier northeastern variants. In the moister centre, where the Warren landform is most common, Inions *et al.* describes the riverine terraces as being occupied by the Havel, the mid slopes by Shea and upper slopes by Beggs community types.

The Havel community type of moist sandy riparian sites has as its key characteristic species *Chorilaena quercifolium, Chorizema diversifolium* and *Lepidosperma effusum*, with *Hovea elliptica* and *Veronia plebeia* also present.

The Shea community types of mid-slopes has as its characteristic species *Bossiaea aquifolium* subsp. *laidlawiana, Chorilaena quercifolia* and *Tremandra stelligera*, with some *Acacia urophylla* also present.

The Beggs community type of well drained sites high in the profile is described as having a significant component of marri (*Corymbia calophylla*) in the overstorey, and *Bossiaea aquifolium* subsp. *laidlawiana, Hovea elliptica, Leucopogon verticillatus, Opercularia hispidula, Pteridium esculentum* and *Tremandra stelligera* in the shrub storey. To a lesser degree there are also *Banksia grandis, Leucopogon australis* and *Lomandra drummondii*.

With decrease in rainfall in the north Strelein's type Q also enters on to this landform. It has yarri (*Eucalyptus patens*), jarrah (*Eucalyptus marginata* subsp. *marginata*), marri (*Corymbia calophylla*) as well as some karri in the overstorey. It has *Persoonia longifolia* in its second storey and its shrub storey includes *Clematis pubescens, Hovea elliptica, Pteridium esculentum, Macrozamia riedlei* and *Tremandra stelligera* and to a lesser degree *Acacia urophylla, Bossiaea aquifolium* subsp. *laidlawiana, B. linophylla* and *Hakea amplexicaulis*.

Although two strongly contrasting landforms, namely the Bevan landform of the largely undissected uplands and the Warren landform of strongly dissected major valleys were chosen as examples of integration between vegetation and landform, there is still some degree of overlap in terms of the individual species. The dominant vegetation type of the Bevan landform is jarrah-marri open forest and the dominant vegetation type of the Warren landform is karri tall open forest, yet at their interface the edaphic and vegetative differences diminish. There is a significant proportion of species that respond primarily to the climatic differences, such as *Hovea elliptica, Leucopogon verticillatus, Bossiaea aquifolium* subsp. *laidlawiana, Clematis pubescens* and *Pteridium esculentum*, so that they occur at the interface of the Bevan and Warren landforms in the high rainfall zone in the west, but are largely absent from the Bevan landform in the low rainfall zone at the eastern margin of the bioregion.

It will be also seen that within the Warren landform the difference in the composition of the shrub storey between Inions *et al.* (1990b), Havel community type of the valley floor and the Beggs community type of the upper slopes is greater than the difference between the Beggs community type and the T vegetation type of Strelein (1988) on the adjacent Bevan uplands. This is so because within a dissected plateau landscape the maximum variation in soils and vegetation is across valleys, and least on the uplands.

The remainder of the information obtained firm matching ecological classifications with landform maps is contained in Appendix D.

At the map scale of 1:250,000, used here for the mapping of vegetation complexes, the width of the Warren landform ranges from 5 to 10 mm and other valley landforms, such as Pemberton and Wheatley, are even narrower, yet it is common for them to be composed of two or three vegetation types (communities). The width further decreases at the scale of 1:500,000 used for the mapping of vegetation systems, which is the finest scale at which the Jarrah and Warren bioregions can be mapped together. The mapping of homogeneous plant communities is impossible beyond the scales used by Havel (1975b), namely 1:50,000 or 1:100,000. The bulk of detailed floristic mapping in southwestern Australia, done in conjunction with impact assessment for mining and engineering projects, is initially done at the scale of 1:10,000 (Mattiske Consulting Pty Ltd 1996), though the scale may be reduced subsequently.

Construction of Toposequences and Definition of Vegetation Complexes

Construction of Toposequences

In order to be able to tackle the complex task of mapping vegetation at bioregion scale a framework had to be established that could accomodate the greater complexity of environmental and vegetational continua. A format of recording that would make comparison across these continua feasible also had to be found.

Such format needed to provide for the display of all relevant physical and biological factors and of the interaction between them in a compact form. The pictorial component of the format follows the pattern already previously utilized by Speck (1958), Havel (1968, 1975b) and Beard (1981) to illustrate the ecological relationships, that is the configuration of the land and the structure and composition of the vegetation. This is augmented by a brief description of climate and soils in terms of criteria most relevant to plant ecology, in particular the water balance, and by description of the composition of the dominant stratum, of the second story and of the shrub and herb story. This format makes it possible to get a rapid overview of similarities between the various vegetation/climate/landform combinations. For the sake of brevity these records of vegetation/climate/landform combinations in the form of diagrams and the associated text will be referred to as toposequences (ecological profiles) in subsequent discussions because of their similarity to toposequences in recent Canadian forest ecology studies.

For bulk of the observations toposequence information is recorded in triplets. For the landforms that are defined more narrowly, such as on the maps compiled by the Department of Agriculture, each component of the triplet generally contains one narrowly defined landform, and the triplet thus depict the interrelationship between neighbouring landforms. Where the landforms are defined more broadly, such as such as on the maps compiled by the CSIRO, the entire triplet is sometimes required to depict the full range of variation within one landform.

There was an unavoidable variation in the way that toposequences were compiled. Where the relationships between climate, landform and vegetation were already well documented, such as in the northwestern Darling Plateau covered by earlier detailed studies of Havel (1975a,b), Heddle *et al.*(1980) and Bettenay *et al.* (1980), the toposequences are either representations of the published information, or additional observations at the extremes of the climatic range.

Where vegetation classifications and landform maps have been published, but the interrelationship between the physical environment and the vegetation has not been adequately established by quantitative studies, the toposequences aim to illuminate these relationships and establishing a link between the ecologist's brief description of the landforms associated with a given vegetation type and the geomorphologist's brief description of the vegetation perceived to be associated with a given landform. This is particularly important for landforms that have a wide geographic spread across several climatic zones, as the tendency has been to focus on the typical or common combination of landform and vegetation, and to overlook that the relationship may be modified by a shift in climate. In this category the toposequences are either interpretations of the published descriptions of vegetation in terms of landform and climate, or new observations of vegetation based on landform and climate maps, the latter being oriented towards exploring the full geographic range.

At the level of the vegetation complexes the aim was to reduce or eliminate the effect of climate, which operates on the widest scale. As described in the previous section, the strategy employed was to subdivide the landforms that were geographically most extensive, into subsets which were as far as possible climatically homogeneous in terms of the annual rainfall/summer evaporation criteria. By doing this it was hoped to reduce the first stage of multiple correlation between factors of the environment and the vegetation to simple correlation between vegetation and landform.

As the climatic boundaries derived by discounting of annual rainfall by summer evaporation are only an approximation, excessive fragmentation of the landforms was avoided by subdividing upland landforms along streamlines and valley landforms along divides closest to the boundary. That portion of the landform having the optimum climatic conditions (hyperhumid-perhumid) was given the suffix 1, e.g. BE 1, that with intermediate conditions (humid-subhumid) suffix 2 and that with the greatest climatic stress (semiarid-arid) the suffix 3.

The importance of the climatic subdivision of the landforms can be seen in the case of such widespread landform as Wheatley, which is described by Churchward (1992) as upstream valleys incised 20-40 m into the southern Darling Plateau. In the perhumid zone near Pemberton (WH1) the vegetation of the slopes is karri-marri tall open forest with second storey of *Allocasuarina decussata, Agonis flexuosa, Banksia grandis* and *Persoonia longifolia*, and tall shrub storey of of *Trymalium floribundum, Tremandra stelligera, Hovea elliptica, Bossiaea aquifolium* subsp. *laidlawiana, Lasiopetalum floribundum, Clematis pubescens* and *Pteridium esculentum*, corresponding to Inions *et al.*'s (1990b) types Shea and Beggs. In the humid-subhumid zone immediately east of Manjimup the slopes of the same landform (WH 2) supports open forest of marri, yarri and jarrah, with second storey of *Banksia grandis, Persoonia longifolia, Agonis flexuosa* and *Hakea oleifolia* and understorey of *Trymalium floribundum, Tremandra stelligera, Hovea elliptica, Bossiaea aquifolium* subsp. *laidlawiana, Lasiopetalum floribundum, Clematis pubescens, Macrozamia riedlei, Leucopogon capitellatus, Leucopogon verticillatus, Phyllanthus calycinus* and *Pteridium esculentum*, corresponding to Strelein's (1988) site types Q, U and V. In the driest variant in the semiarid-arid zone (WH 3) the slopes of the landform support woodland of wandoo and marri, largely without second storey and with understorey of *Macrozamia riedlei, Hakea lissocarpha, Leucopogon capitellatus* and *Trymalium ledifolium*, corresponding to +C1 and +C2 of Christensen's (1980) ordination.

Where no published classification of vegetation existed, or where landform mapping was proceeding concurrently with vegetation mapping and the description of landforms was as yet unavailable, the toposequences represent new observations. In such a case they were intended to form a basis for the description of new vegetation types and for the understanding of ecological relationships, and hence the tendency was to record a greater number of toposequences for a each vegetation/climate/ geomporphology combination. The compilation of new toposequences was often, but not always, carried our concurrently with establishment of detailed quadrats or with field checks on landform boundaries. This was done so as to minimise the duplication of risk and of effort in travel and to provide a sounder taxomomic basis. Even where toposequence compilation was combined with other observations, it was done by separate personel.

Vegetation Mapping – Vegetation Complexes

The vegetation complex maps were developed as an extension of the earlier studies by Heddle *et al.* (1980) in the northern jarrah forest. The boundaries were delineated on base maps at a scale of 1:50,000 recognizing that the maps would be reduced by a factor of 5 or 10 for publication. Although these maps are not included in this publication, this base mapping at the scale of 1:50,000 is available at the Department of Conservation and Land Management and has already been used for forestry planning and management activities.

In mapping the vegetation complexes, the line work was based on the underlying topography, field observations, detailed data as available for specific sites throughout the south west forest region and the underlying landform and soil units as defined by various authors, but as rationalized by Smolinski (1999). The range of catennas available on the range of subregions enabled a clarity in the vegetation mapping process that would not have been feasible in the time frame allocated without the previous studies by other authors (as outlined in the previous text).

The vegetation mapping was undertaken by Mattiske and Havel. The design of the mapping colouring system was undertaken by Mattiske and was based on the earlier chromatograpy concepts presented by Gentilli in his development of the chapter in Western Landscapes (Gentilli 1979b). All the digitising and map preparation tasks were undertaken by the computing cartographic section of the Department of Conservation of Land Management.

In areas where the vegetation was clearly related to the underlying site conditinsthe vegetation complex name followed the underlying landform and soil mapping unit; however where the climate varied substantially across the same underlying landform and soil mapping unit the unit was subdivided. An example of the latter split can be seen in the subdivision of the Dwellingup unit into four units D1, D2, D3 and D4; with D1 occurring in the hier rainfall areas on the western part of the Darling Ranges and D4 on the lowe rainfall areas on the eastern part of the Darling Ranges. The differences in these four units can be seen not only in the shift of the structural components from an open forest to a woodland, but also in the dominance and composition of both the overstorey, second storey and understorey species (eg. Appendix D). In other instances, where extreme localized sites were restricted in area (eg. the ironstones on the fringes of the Blackwood Plateau and sections of the Scott Plain) it was necessary to combine some mapping units. In most instances, the latter variation is included in the summaries within Appendix D or has been covered by previous studies by specific authors in local studies. The latter reflects the difficulty of capturing all the variation at a regional scale of mappin.

Description by Toposequences

A toposequence is an attempt to capture the essence of the relationship of vegetation to a particular combination of climate and landform, rather like a snapshot. Each toposequence contains verbal description of climatic zone and general location in which it was captured, of the soil structure and hydrology, and of the composition of the understorey, as well as verbal and pictorial description of the topography and of the structure and composition of the overstorey and second storey. As such it gives a basic description of a vegetation complex. The fullest description of a vegetation complex is provided by the sum of the toposequences that describe that combination of climate, landform and vegetation, rather like a folder containing all relevant snapshots. A set of toposequences depicting the same climate/landform combination enhances the description either by reinforcing it or by defining the range of variation within the vegetation complex.

Whereas in System 6 Heddle *et al.* (1980) the vegetation complexes were described in terms of the component site-vegetation types, in this RFA study the vegetation is described in terms of the component species, that is, the dominant and subdominant trees and characteristic (indicator) or common species of the understorey. The reason for this is that in this project the level of knowledge across all the various underlying landform maps and vegetation classifications is uneven and diverse, and for many of the complexes there is no previous classification to refer to. Whereas in System 6 vegetation complexes were the highest level of hierarchy, in this project the vegetation complexes are ultimately agglomerated into ecological vegetation systems. They are therefore viewed here more as the stepping stones rather than terminals. At the level of the vegetation complex the observation is made, and at the same time the hypothesis is stated, that for a given combination of climate and landform a certain set of species is likely to occur. The next step in the process is the examination of the vegetation complexes to see which of the vegetation complexes are sufficiently similar to warrant agglomeration into ecological vegetation systems. It is at this more general level of ecological vegetation systems that the various underlying classification units (types, communities, groups) are brought in, if available.

Description by Map Legend

Description by map legend is the most concise form of description, as space is at premium. It is an attempt to summarize the essence of a map category, in this case a vegetation complex, characteristic of a given combination of landform and climate, in a few short lines.

The definition of the mapping units and hence the compilation of the map legend was based on the toposequences illustrating the vegetation/climate/geomorphology combinations. It needs to be realized that at each stage of the process of developing a higher and more complex, yet at the same time more concise concept, such as the fusing of the landform, climate and vegetation information into a toposequence depicting a vegetation complex, there is an inevitable loss of information. This is heightened when a full description of the resulting categories is condensed into a map legend. The risk entailed in that is that the loss of information may be so high as to make the condensed description too brief and too general and hence open to criticism of imprecision and vagueness. The study of the map therefore needs to be done with this process in view, that is by augmenting the reading of the map legend by the reading of the accompanying text, and if necessary, going back to the underlying level of mapping and description. In the case of the vegetation complex this means going back to the toposequences, and perhaps even back to the underlying landform maps and vegetation classifications.

The legend describing all vegetation complexes described for the Jarrah and Warren bioregion is printed on the maps of the vegetation complexes attached.

Agglomeration of Vegetation Complexes into Ecological Vegetation Systems and Their Description

The ecological vegetation systems were developed by Havel and Mattiske (1999) on the completion of the vegetation complex maps and the development of the hierarchial system as defined in linkages by Mattiske Consulting Pty Ltd (1996) – [redacted] and Appendix C. Havel and Mattiske then developed these relationships between determining factors of landforms, soils, climate and resultant vegetation into the development of the ecological vegetation systems, which apporximate the ecological vegetation classes as developed in the Victorian RFA process by Peel and his team of ecologists. The latter mapping has since been tested by Havel using the State Herbarium Florabase as part of his doctorate (Havel 2000).

The merging of the vegetation complexes into the ecological vegetation systems was undertaken by the Department of Conservation and Land Management mapping team under guidance from the authors.

In the agglomeration of vegetation complexes into ecological vegetation systems the principle of near-equivalence was used to combine Mattaband (MTy1), Collis (Coy1) and Bevan (Bey1) into lateritic uplands in the hyperhumid to perhumid zone, Dwellingup (D1) and Hester (HR) into lateritic uplands in the humid zone, Dallmore (DM2) and Sandalwood (SD) into lateritic uplands in subhumid to semiarid zone.

It will be seen that in the systems where the biologically significant factors were expressed at the subsystem level by the affixes (y for gravelly yellow duplex soils and 1 for hyperhumid-perhumid climate), such as in Collis, Mattaband and Bevan, we combined edaphically and climatically equivalent subsystems to generate vegetation systems. These vegetation systems, which are intended to be biologically homogeneous, are not the same as landscape systems, in which the accent is on geographic proximity and recurrent topographic and edaphic patterns.

Regretably, in the yet unpublished landform surveys of the southeastern region, the affix 1 stands for edaphic factors – gravely yellow duplex soils with lateritic outcrop. As the three systems all occur only in the arid zone, no climatic affix is needed. Boscabel (Bo1), Darkan (Dk1) and Farrar (Fa1) can thus be combined into lateritic uplands in the arid zone.

Basis for Agglomerating Vegetation Complexes into Vegetation Systems

The loss of information that accompanies generalisation, which was described earlier with respect to the formulation of vegetation complexes, is even more acute in the case of the fusion of several vegetation complexes into one vegetation system.

Correspondingly, the need to refer to the underlying sources when studying a map is particularly acute in the case of the ecological vegetation systems, where this means going back to the vegetation complex level, and may be even to the landform maps and vegetation classifications on which the vegetation complexes are built.

An example of full length description of vegetation systems is given in Appendix 3.7. An example of medium length description is given in Table 3.4.

Definition of the Mapping Units

The definition of the vegetation systems is largely a desk top exercise, as the components of a vegetation system may be scattered over hundreds of kilometres. Essentially it consists of a search for similarities between vegetation complexes, and evaluation of these similarities so that a decision can be made whether or not to merge two or more complexes into a ecological vegetation system. The initial search was done on the basis of toposequences, which provide a combined pictorial and textual description of the vegetation complexes. The search was guided by the description of the underlying factors of the physical environment, as the most likely mergeable components are those that share similar combination of landform and climate. This can be looked upon as the deductive component of the process. The final decision to merge was, however, done on the basis of the structural and floristic features of the vegetation, because what ultimately counts is whether there is sufficient similarity in vegetation to justify the merger. This can be considered the inductive component of the process.

On the whole the two processes did not lead to divergent conclusion. It was, however, found that if the accent was too much on the underlying physical factors of the environment, the agglomeration proceeded too rapidly and resulted in categories that were too broad and too heterogeneous in terms of vegetation. If the initial accent was too much on vegetation, the process became too laborious and too slow. This is because the differences between vegetation complexes amount to subtle variations in structure and floristic composition. The comparison of floristic composition requires the consideration of a relatively large number of component species. Consequently, after the initial trials the two processes were used jointly.

A further complicating factor arose out of the characteristic of vegetation complexes already discussed, namely that they tend to be continua rather than narrowly defined entities. Whereas it is a relatively easy to agglomerate two or more vegetation complexes into an ecological vegetation system, it is very difficult to reverse the agglomeration process if it has gone too far. Ultimately, a cautious approach was adopted. It may be that some vegetation systems that occupy only small areas could have been agglomerated with larger ones, thus reducing the relatively large number of vegetation systems. Such agglomeration would have also reduced the disparity of size between the vegetation systems, some of which occupy much smaller areas than others. The potential risk of eliminating ecosystem small in extent, but significant floristically, was considered to be too great.

Yet another difficulty encountered was the delineation of the geographic limits of some of the more common combinations of environmental and structural criteria. For instance, the open forest of jarrah-marri occupies the bulk of the lateritic uplands in the humid-subhumid zone of the Darling

Plateau over a distance of 500 km. Yet the composition of the understorey varies gradually but significantly. To put all of this into one vegetation system would defeat the objective of this project. Again, the potential risk of eliminating floristic variation was considered unacceptable.

It also proved difficult to relate all of the 300+ vegetation complexes to each other simultaneously, particularly as many of them have no common boundaries with one another, and do not appear together on the toposequences.

For these reasons several attempts at sub-regionalisation were made, some of which foundered on lack of clear cut boundaries. The approach ultimately adopted used the two most extensive and most consistent geographic features of the southwest, namely the Darling Scarp and the Blackwood River. The Darling Scarp was used as a north-south boundary and the margins of the Blackwood River catchment as the east-west boundary. The four sub-regions thus are:

- Western - west of the Darling Scarp, including the Scott Coastal Plain, Margaret River Plateau, Blackwood Plateau and the Southern Swan Coastal Plain

- Southern - east of the Darling Scarp, south of the Blackwood catchment, including the Southern Coastal Plain and Hinterland, the Southern Darling Plateau and the Unicup Basin

- Central - Blackwood and Preston catchments east of the Darling Scarp

- Northern - east of the Darling Scarp, north of the Blackwood-Preston Catchments, consisting of the northern Darling Plateau and the Collie Basins.

The small fragments of the Northern Coastal Plain and the Dandaragan Plateau occuring west of the Darling Plateau but included within the project area were dealt with as subsets of the Northern sub-region.

The process of agglomeration was carried out by sub-regions, commencing at the wettest margin (coast or escarpment) and proceeding inland to the driest margin.

In the legend for the map of the Ecological Vegetation Systems the Western and Southern sub-regions, which both contain karri forests, coastal dunes and coastal swamps and plains, were dealt with jointly for economy of description. Similarly the Central and Northern sub-regions, which consist mainly of the dissected western margin of the Darling Plateau carrying jarrah forest, were dealt with jointly.

Within the Southern and Western sub-regions the agglomeration commenced with the hyperhumid foredunes and progressed through the stable older dunes to the sub-coastal swamps and plains, inland swamps and river valleys to the slopes and uplands of the plateau, ending with the semi-arid uplands at the eastern margin of the project area. Within the Central and Northern Region, which occur inland, the agglomeration commenced with the steeply sloping escarpment and major valleys at the wet western margin of the Darling Plateau, through progressively milder inland valleys to swamps in the headwaters of the streams and finally to uplands of increasing aridity, ending with semiarid to perarid uplands on the northeastern margin of the project area. The sedimentary basins or plateaus were dealt with separately from the crystalline plateaus because of their bias toward sandy infertile soils and subdued topography.

Examples of the Agglomeration Process from Southern Subregion

Coastal Vegetation Systems

Basically, the first step in agglomeration was to search for possible match between the landform categories defined by the various surveys on which this study was based, that is, whether categories defined by different geomorphologists were sufficiently similar in terms of vegetation to warrant agglomeration. For instance, the dune systems at the southwestern margin of the project area were named Meerup east of the southern tip of the Darling Scarp by Churchward *et al.*(1988) and D'Entrecasteaux by Tille and Lantzke (1990) west of it. Within each dune system several subsets (landforms) were defined on the basis of degree of stabilisation and soil formation, e.g. Mu, Mc, Mr, My, Ms and Mf in the case of Meerup and D5, Dd5, DE5, Drd and Dr in the case of D'Entrecasteaux. Further to the west, north and west of the Blackwood River estuary, yet another two dune systems were described, namely Kilcarnup and Gracetown, subdivided into Kef, Kf, Kr, Ge, GE, G2, G3, Gv and Gk. Whilst the four dune systems differ in terms of geomorphology and geographical setting, the subsets (landforms) within each system often have less in common in terms of plant cover than they have with the corresponding subsets of the neighbouring systems. The sources available on vegetation classification and mapping, namely Smith's (1972,1973) and Beard's (1981) maps based on structural criteria, and Gibson's (personal communication) floristic classification, do not make a clear distinction between the four dune systems. Wardell-Johnson *et al.*'s (1995) classification is confined to a relatively small portion of the coast near Walpole.

Churchward's (1992) landform maps straddle the Meerup and D'Entrecasteaux systems, and hence form a link between Churchward *et al.*(1988) and Tille and Lantzke (1990). They also have a reasonable description of the vegetation associated with the various subsets. Churchward (1992) was therefore used as the basis for linking the landforms across systems and landforms and vegetation within and across systems. Gibson (personal communication) was used for more detailed floristic descriptions and Beard (1981) and Smith (1972,1973) for structural descriptions. These sources were supplemented by additional sampling both in terms of sample plots and toposequences.

At the first level of agglomeration, vegetation complexes Mc,Mp, Mr and My within the Meerup dune system, were combined into vegetation system Py9, which stands for mixed coastal heath or low woodland of *Agonis flexuosa* (P-peppermint) on young but stabilised dunes (y) of the hyperhumid (9) south coast. This contrasts with the vegetation system Qu9, consisting of vegetation complex Mu, which occurs in the same dune system but differs in being a mosaic of bare sand, sometimes stabilised with *Ammophila arenaria*, and of mixed coastal heath (Q) on unstable dunes (u) in hyperhumid zone (9). It also contrasts with Po9, which combines Ms and Mf vegetation complexes and describes woodland of *Agonis flexuosa* (P), *Eucalyptus cornuta, Eucalyptus megacarpa* and *Banksia attenuata* or open forest of *Eucalyptus marginata* subsp *marginata* and *Corymbia calophylla* with *Agonis flexuosa* second storey. It occurs on old (o) leached stable dunes and in swales, generally further inland than Py9, but still in the hyperhumid zone (9).

The degree of generalisation involved is best seen by comparing it with floristic classifications of Gibson (personal communication) and Wardell-Johnson *et al.* (1995). In terms of geographic position and description of structure several of Gibson (personal communication) community groups occur in the Py9 vegetation system, namely communities 4,5,7, and 9. Between them they contain many tens of species of shrubs and herbs and a few trees, some of them shared across several communities, others specific to one community. The common coastal species occurring in most of these communities are *Agonis flexuosa, Acacia littorea, Olearia axillaris, Spyridium globulosum, Poa poiformis, Leucopogon parviflorus, Rhagodia baccata, Hibberia grossulariifolia, Lepidosperma angustatum, Loxocarya flexuosa* and *Phyllanthus calycinus*. The differences between the groups reflect edaphic variation that occurs within the stable younger dunes, from group 4 on skeletal limestone containing *Lepidosperma gladiatum, Podotheca angustifolia, Poa drummondii, Stipa flavescens, Thomasia triphylla, Olax phyllanthes* and *Melaleuca acerosa* through community group 7 on deeper sands containing *Hibbertia cuneiformis, Hardenbergia comptoniana, Tetrarrhena laevis* and *Macrozamia riedlei* to community group 9 containing *Jacksonia horrida, Lobelia tenuior, Levenhookia pusilla, Waitzia citrina, Brachysema praemorsum, Amperea ericoides, Xanthosia huegelli* and *Sollya heterophylla*. Similarly, this vegetation system corresponds to Wardell-Johnson *et al.*'s (1995) community groups 14 to 17, containing a smaller (30-40) group of species of high constancy, including *Agonis flexuosa, Sollya heterophylla, Leucopogon parviflorus, Hibbertia cuneiformis, Hibbertia grossulariifolia, Lobelia tenuior, Lepidosperma angustatum, Waitzia citrina, Olearia axillaris, Spyridium globulosum* and *Acacia littorea*.

At the second level of agglomeration, carried out by colour and legend, Py9 was grouped, but not merged with Py8 of the D'Entrecasteaux dune system and Py7 of the Kilcarnup and Gracetown dune systems on the basis that they all carry mixed coastal heath and low woodland of *Agonis flexuosa* on young but stabilised dunes. The numerical affixes reflect the climatic zone, namely humid (7), perhumid (8) and hyperhumid (9).

Inland Vegetation Systems

There appears to be no clearcut division, from the point of view of geomorphology or vegetation, between some of the southern valley landforms described by the various authors. The vegetation at the extremes is distinct, e.g the presence of the tingles in the southeast near Walpole only. The vegetation complexes Vh2 and Vh3 north of Northcliffe, based on the V2 and V3 landforms of Churchward *et al.* (1988) have, in terms of overstorey, more in with common with the Warren and Lefroy vegetation complexes based on Churchward (1992), to the north and west of them, then with the vegetation complexes Vh2 and Vh3 near Walpole. For this reason, the four vegetation complexes were agglomerated on the basis that they all carry tall open forest of *Eucalyptus diversicolor - Corymbia calophylla* on moderate to steep slopes with red earths and red duplex soils in perhumid-hyperhumid climate. They also have a similar second storey of *Allocasuarina decussata* and *Agonis flexuosa* and similar understorey vegetation of *Trymalium floribundum, Chorilaena quercifolium, Tremandra stelligera, Hovea elliptica, Bossiaea aquifolium* subsp. *laidlawiana, Lasiopetalum floribundum, Clematis pubescens, Chorizema diversifolium, Pteridium esculentum* and *Opercularia volubilis*. The Walpole occurrences of the Vh2 and Vh3 complexes also have *Eucalyptus jacksonii* and *Eucalyptus guilfoleyi* as associates. The Donnelly vegetation complex, which is restricted to a steeply dissected valley close to the western margin of the Darling Plateau, and the V1 complex restricted to steep valleys in the south coast hinterland, were also added to this vegetation system.

The corresponding community types of Inions *et al.* (1990b) are type No 11 (Havel) with *Chorilaena quercifolia, Chorizema diversifolium, Lepidosperma effusum, Logania vaginalis, Hovea elliptica, Opercularia volubilis, Veronica plebeia* on the valley floors, type No 6 (Wallace) with *Chorizema ilicifolium, Crowea angustifolia* var *dentata, Lepidosperma effusum* and *Anigozanthus flavidus*, on slopes in the south, and type No 10 (Shea) with *Bossiaea aquifolium* subsp. *laidlawiana, Chorilaena quercifolia, Tremandra stelligera* and *Acacia urophylla* on the slopes in the north. The corresponding community groups of Wardell-Johnson *et al.* (1995) are 42 and 37, which share *Eucalyptus diversicolor, Chorizema retrorsum, Dampiera hederacea, Allocasuarina decussata, Lasiopetalum floribundum, Leucopogon verticillatus, Tetrarrhena laevis, Tremandra stelligera, Pteridium esculentum* and *Clematis pubescens*. They have, in addition, *Corymbia calophylla, Lepidosperma effusum, Lepidosperma leptostachyum, Thomasia quercifolia, Hovea* *elliptica* and *Eucalyptus guilfoleyi* in the case of 37 and *Chorilaena quercifolia, Trymalium floribundum* and *Eucalyptus jacksonii* in the case of 42.

In the inland of the Southern sub-region Strelein's (1988) and Wardell-Johnson *et al.*'s (1995) vegetation classifications were utilised in interpreting the landform mapping of Churchward *et al.*'s (1988) in the southeast, Churchward's in the west and Smolinski (1999) in the northeast. Inions *et al.*'s (1990b) classification was only relevant for the for the more humid south and west and Christensen's (1980) classification was only relevant for the drier centre and east. Whilst there was some degree of overlap between the vegetation classifications in the southwest and centre, none of the classifications adequately covered the northeast, and the fieldwork done there was consequently at a higher level of intensity to compensate for this deficiency.

Agglomeration in the western, central and northern subregions

In the Western sub-region the aim was to bring together similar vegetation complexes based on the Mc Cutcheon (1980) classification of the northern Blackwood Plateau, on Gibson's (personal communication) classification of the western and southern coasts and adjacent coastal plains, on Gibson *et al.*'s (1994) clasification of the southern Swan Coastal Plain and its transition to Blackwood Plateau and on Mattiske Consulting Pty Ltd's (1996) surveys of parts of the Scott Coastal plain. The main deficiency was the lack of vegetation classification for the ecologically very diverse Margaret River Plateau, and consequently the fieldwork was more concentrated here, hindered by high level of land alienation and conversion to agriculture. This was compensated for to a degree by Griffin's (1995) surveys of remnant vegetation on private land. The Margaret River Plateau proved, in ecological terms, to be a miniature outlier of the western margin of the southern Darling Plateau, having forests dominated by both jarrah and karri. In the agglomeration process, the vegetation systems of the Margaret River Plateau were grouped with, but not merged with vegetation systems of the southern Darling Plateau.

In the Central sub-region no previous quantitative vegetation classification could be refered to, though it was known from earlier mapping of the System 6 (Heddle *et al.*, 1980) which covered part of the sub-region, that it is largely an extension of the Northern sub-region. However, it has a higher degree of dissection and hence a higher proportion of fertile soils. It is also much more highly disturbed by agriculture, and it proved difficult to find undisturbed examples of adequate size for many of the landforms which are attractive to agriculture because of their higher soil fertility. Havel's (1975a) classification from the north of the sub-region and Strelein's (1988) classification from south of the sub-region were therefore utilised and supplemented by intensive field sampling of residual vegetation. This was further supplemented by Griffin's (1995) surveys of remnant vegetation on private land. Because of the wide climatic range and great fragmentation of the sub-region a higher number of vegetation systems per unit area was retained than in the neighbouring sub-regions.

In the Northern sub-region less agglomeration was carried out than in the other three sub-regions. The primary reason for this is that this region was the first to be mapped in terms of landforms, at a coarser level than the other sub-regions (Mulcahy *et al.* 1972; McArthur *et al.* 1977; Churchward and McArthur 1980). Consequently, the landforms and the vegetation complexes based on them are broader in concept and more extensive in area than in the later surveys. Although more detailed landform mapping was subsequently carried out on the northwestern (King and Wells 1990) and northeastern (Lantzke and Fulton 1992) periphery, it did not cover the entire northern sub-region and it was not possible to use it in the mapping of the vegetation for the sub-region as a whole. Secondly, in the earlier mapping of (Heddle *et al.* 1980) a great deal of on-the-ground reconaissance was carried out in the northern sub-region, which could not be matched in the present round of mapping, particularly as the focus was on the central, southern and western sub-regions which lacked earlier maps. The tendency has therefore been toward minimal modification of the mapping of Heddle *et al.* (1980). However, much fieldwork was carried out in the eastern margin of the sub-region not covered by earlier mapping, and the detailed vegetation classification in the extreme north of the sub-region by Griffin (1992) was utilised.

The ecological vegetation systems of the Northern sub-region tend to be more extensive in terms of area/system, and less precisely defined than those of the other three sub-regions. On the positive side, much greater proportion of the Northern sub-region is covered by detailed vegetation mapping at the level of site-vegetation type of Havel (1975a,b), carried out in conjuction with research, reserve establishment, disease control, mining and water resource development (E.M. Mattiske and Associates 1991; Worsley Alumina Pty Ltd 1999; Havel Land Consultants 1987; Shearer *et al.* 1987). Some of this is now historical information, as the natural vegetation was subsequently eliminated by surface mining or flooding or significantly altered by the impact of the dieback disease.

Conclusions

The compilation of the maps and the supporting legends, descriptions and illustrations brings the process of integrating the various vegetation classifications and landform and climate maps into one ecological map of the entire forested area of south western Australia to conclusion. Because the information sources are so diverse, the process was unavoidably complex, cumbersome and subjective.

The resulting six maps of vegetation complexes and one overall map of ecological vegetation systems match the definition of ecological map in that they combine vegetation and the underlying environmental factors. They are somewhat unique in that they are essentially maps of continua. At the highest level, the broad patterns are determined by climatic zones, which range from hyperhumid on the south coast to perarid inland north east. This continuum is broadly expressed in a range of colours from blue and mauve through green and yellow to red. Although the individual vegetation complexes are discrete polygons on the map, together they represent several continua, such as that from steep slopes with shallow loamy soils (He2) to near level swampy depressions (Swd). This continuum is broadly expressed in intensity of colouring, in that steep slopes are dark coloured and level depressions light coloured.

The maps are the first to attempt to map the floristics of the vegetation at the scales of 1:250,000 and 1:500,00. The map of the vegetation systems is the first overview of the two bioregions combined.

The process whereby the maps were developed, that is through a "bottom-up" approach of inductive agglomeration differs from the usual "top-down" approach of deductive definition of map categories through division of the whole into hierarchically arranged sub-units.

Vegetation Mapping of the South West Forest Region.
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Fig 3.1 a

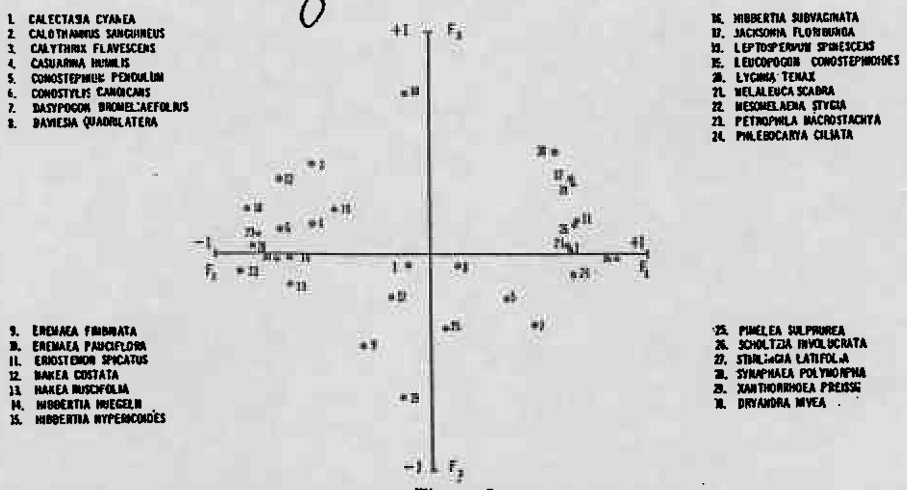


Figure 8.
First stage of output from factor analysis programme, that is, the loadings of the 30 species used in the analysis on the first and third factors.

3.1.b

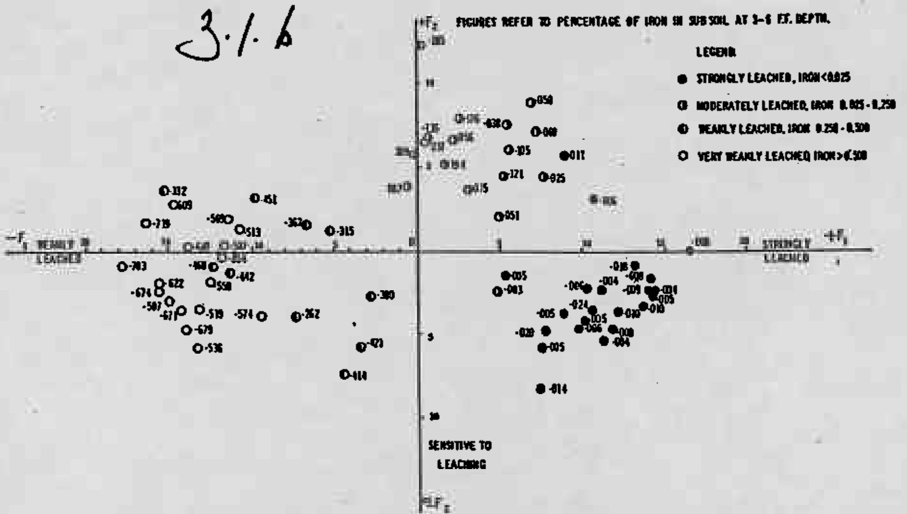


Figure 9.
Second stage of the factor analysis, that is, the plot factor scores on the first and second factor. The figures for each plot represent the mean percentage of iron in the subsoil.

Fig 3.6

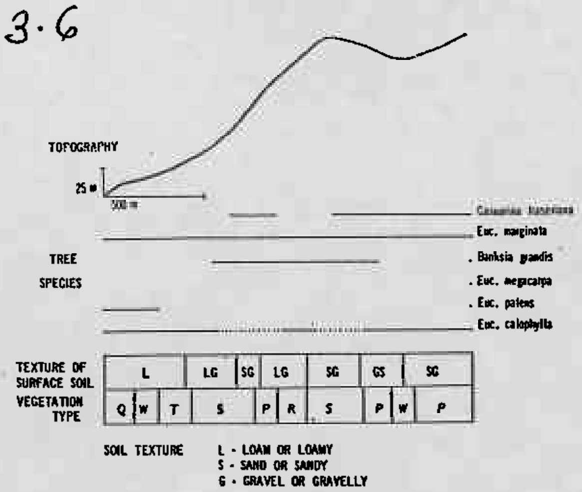
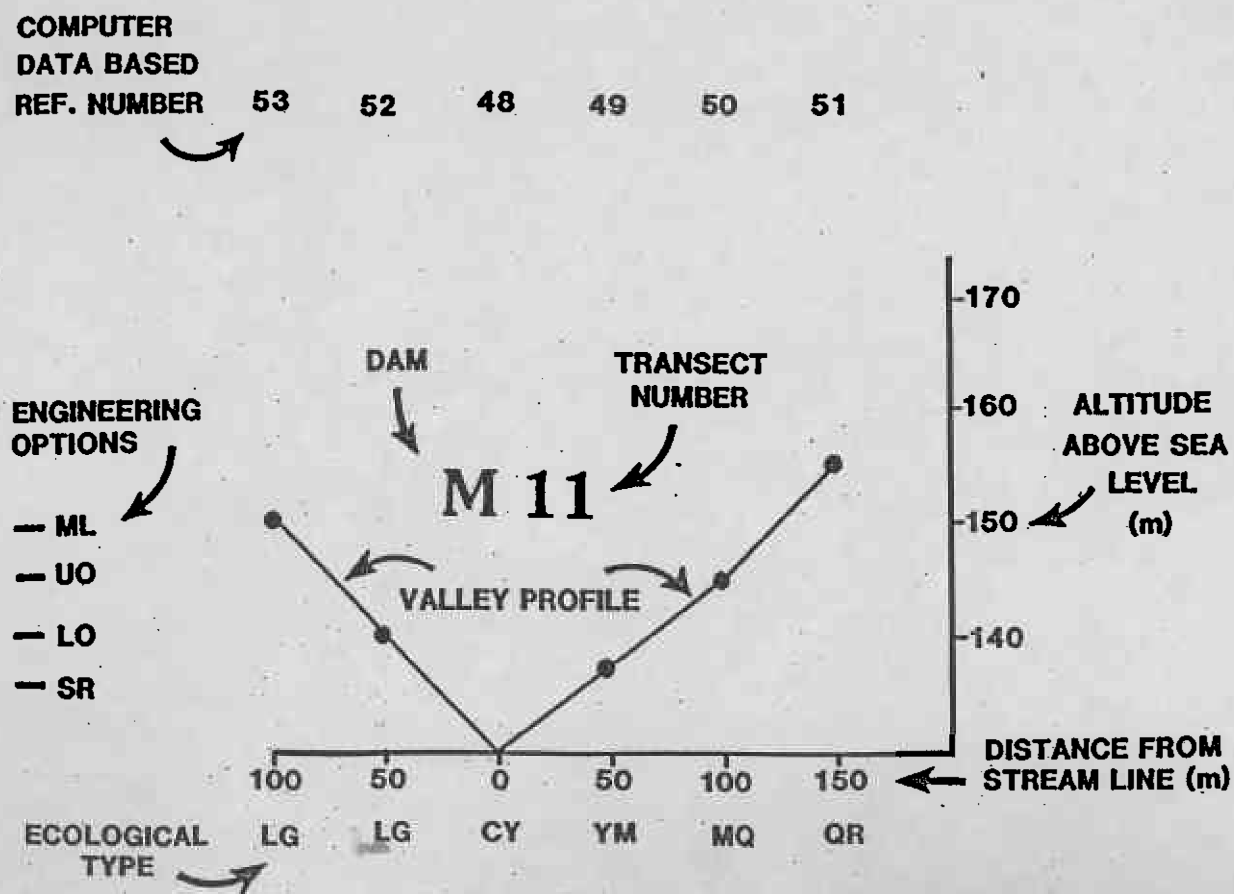


Figure 40

Topographic, edaphic and vegetational transect through the northern sector of the Ashendon Test Area. (Lateritic uplands and Darkin-type valley in high-rainfall zone).

. INTEGRATION OF THE GEOGRAPHICAL, ENGINEERING AND ECOLOGICAL FEATURES OF THE DATA BASE.

INTEGRATION OF THE DATA BASE



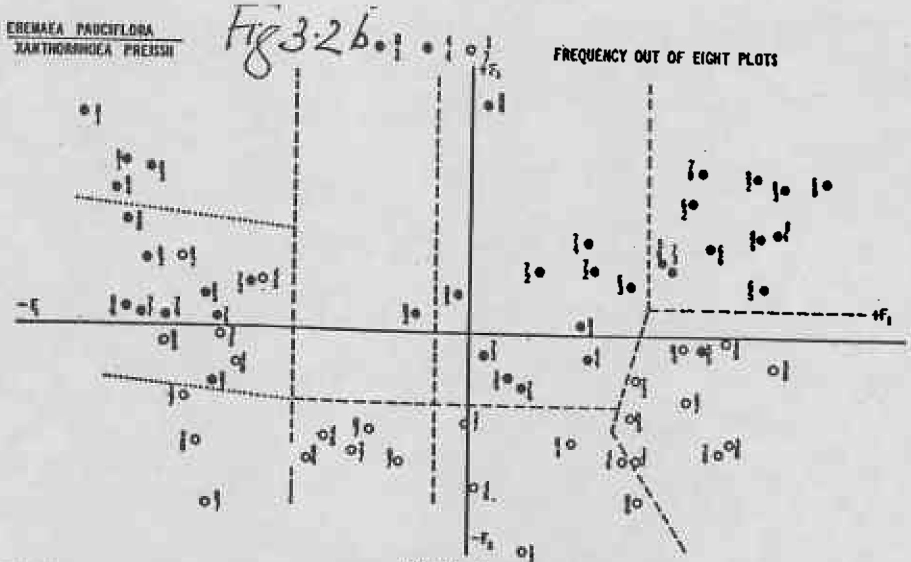


Figure 14.
Distribution of two shrub indicator species within the factor space. The species are those with the highest positive and highest negative loadings on the third factor, that is, with the highest sensitivity to soil moisture availability. The figures refer to mean frequency out of a set of eight 13 ft. x 13 ft. sub-plots.

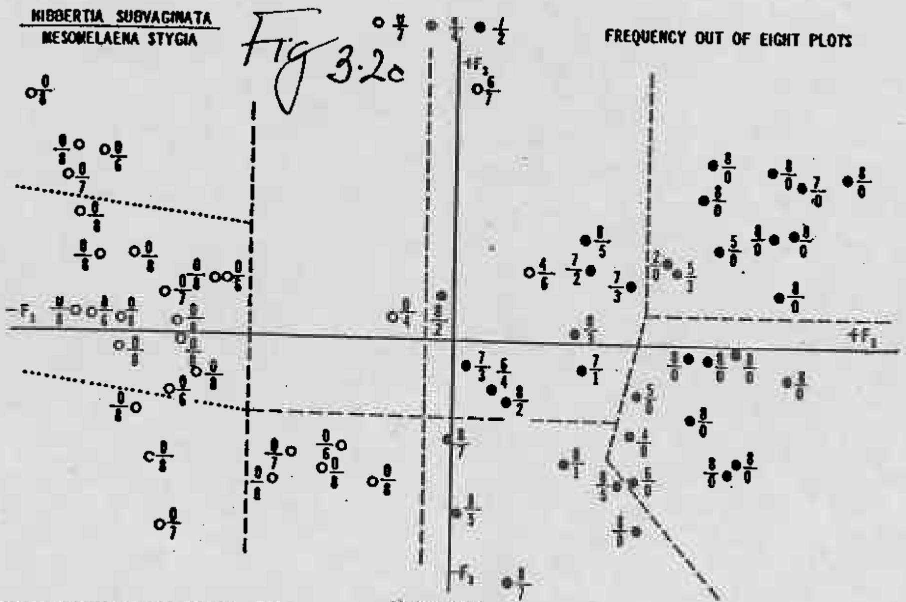
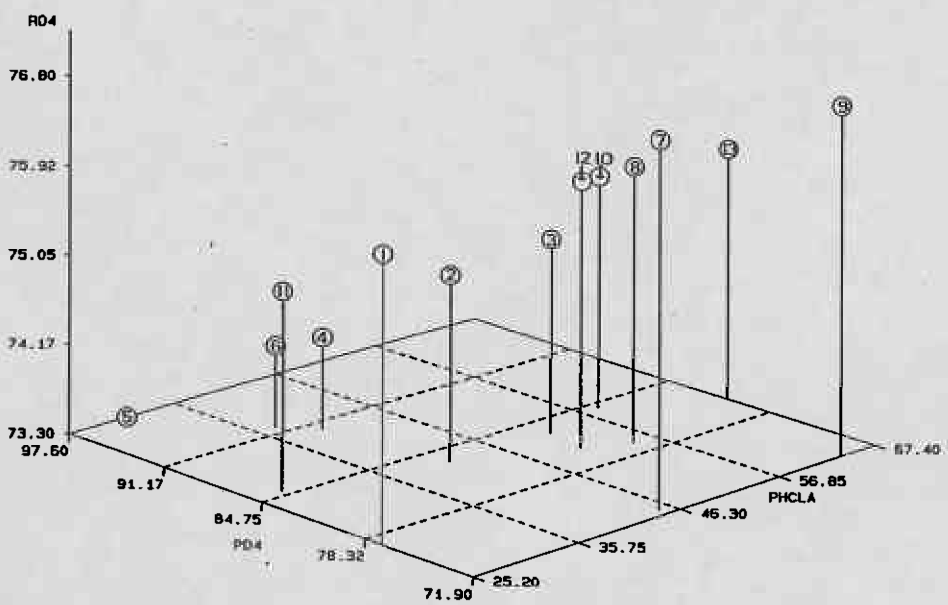


Figure 13.
Distribution of two shrub indicator species within the factor space. The species are those with the highest positive and highest negative loadings on the first factor, that is, with the highest sensitivity to the leaching of soil. The figures refer to mean frequency out of a set of eight 13 ft. x 13 ft. sub-plots.

FIG 3·7



1 = Ednie-Brown 2 = Lane-Poole 3 = Kessell 4 = Stoate
5 = Harris 6 = Wallace 7 = Stewart 8 = Beggs
9 = McNamara 10 = Shea 11 = Havel 12 = White
13 = Annels

Fig. 3. Position of community-types in 3 dimensional space defined by the mean values for PD4 (precipitation in the driest quarter (mm)), RD4 (radiation in the driest quarter (MJ m^{-2} day^{-1}) and PHCL(A) (phosphorus in the A soil sample (p.p.m.)).