Muresk Institute
Centre for the Management of Arid Environments

Assessing Long-Term Change In Rangeland Ecological Health Using The Western Australian Rangeland Monitoring System

Peter John Russell

This thesis is presented for the Degree of
Doctor of Philosophy
of
Curtin University of Technology

October 2007

Declaration

To the best of my knowledge and belief, this thesis contains no material previously published by any other person except where due acknowledgement has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Candidate signature:

Peter Russell

Submission date: 22 October 2007

FRONTISPIECE

Striking brick-red curly bark of the Miniritchie tree *(Acacia grasbyi)* and conspicuous pink-red flowers and bright green foliage of the Pixie bush *(Eremophilia oldfieldeii)* growing in shallow, non-saline sandy-loam soil over granite in mulga shrubland on Cashmere Downs station, north of Kalgoorlie, Western Australia.

Abstract

The rangelands or semi-arid and arid regions of Western Australia occupy about 87 percent of the land area. Pastoral grazing of managed livestock, mainly sheep and cattle, occurs over much of this area, with an increasing proportion being allocated to the state conservation estate.

Rangeland monitoring began at the local scale in the 1950s and since then has been closely tied to the needs of the pastoral industry. By 1992 a regional-scale, ground-based system was in place after two decades of trialling precursor techniques. The state-wide pastoral monitoring programme, known as the Western Australian Rangeland Monitoring System (WARMS), helps to monitor the state's natural vegetation and soil resources.

Change in soil and vegetation attributes through time, in response to climatic conditions, herbivore grazing, fire and other natural and anthropogenic drivers in the rangelands is known as change in range condition or range trend. When range condition is used in an ecological context, as it is in this research, an improving trend implies an improvement in ecological integrity or ecosystem health. In contrast, a declining trend implies a reduction in integrity, otherwise known as natural resource degradation.

The principal objective of this study is to produce a regional-scale, long-term quantitative assessment of range condition change in the southern rangelands of Western Australia, using WARMS transect data. Previous analyses of the WARMS database have examined selected vegetation parameters, but this study is the first to calculate a single integrated range condition index.

The assessment covers an area of approximately 760,000 km^2, stretching southeast from the southern Pilbara region through the Gascoyne-Murchison and Goldfields regions to the Nullarbor region on the Great Australia Bight. WARMS is designed to provide data and information for assessing regional and long-term changes in rangeland ecological condition. It consists of two principal parts: (1) numerous permanent field monitoring sites and (2) a large relational database.

By the end of 2006, there were 980 WARMS sites located on 377 pastoral leases (stations) in the southern rangelands of Western Australia. Average lease size is 202,190 ha and the largest is 714,670 ha. The total area occupied by leases (pastoral plus leases converted to the conservation estate) is approximately 76,250,000 ha. WARMS sites are at an average density of 2.6 sites per lease or 1 site per 77,780 ha of pastoral rangeland. Field-recorded metrics include 11 soil surface parameters and four plant parameters (location on belt-transect, species, height and maximum canopy extent). The field data collection protocol has remained essentially unchanged since 1992 and new field data are captured at each site on a 5-year cycle. This is the most extensive quantitative, ground-based rangeland monitoring system in Australia.

This assessment of range condition is based a suite of soil and vegetation indices derived from the WARMS transect field metrics. Seven basic indices have been derived and algorithmically combined into three higher-order indices, one for each of three components of ecological integrity: composition, function and structure. The three indices are then combined into an overall index of ecological health called the Shrubland Range Condition (SRC) Index. In addition, the indices have been assigned to particular time-slices based on the field acquisition date of their component metrics, allowing the calculation of change through time. The combination of the hierarchical index framework, the use of time-slices and GIS mapping techniques provided a suitable analysis platform for the elucidation of spatial and temporal change in rangeland ecological integrity or health at WARMS sites. The nature of change in the SRC Index and the landscape function, vegetation structure and vegetation composition sub-indices has enabled possible causes to be inferred.

Abstract

The patterns of range condition and change are complex at all landscape scales. However, based on analysis of the WARMS sites, range condition is considerably more variable, in space and time, in the northern parts of the southern rangelands compared to the southern parts, with the exception of the Nullarbor region.

Through time, the Ashburton and Gascoyne regions consistently demonstrate the largest area (site clusters) of change and the greatest magnitude of change. For many areas, range trend has fluctuated markedly between improvement and decline since the mid-1990s. However, there are two large clusters of sites which show continuing decline through more than two decades. The legacy of historical degradation and ongoing poor land stewardship (principally through over-stocking) is hindering the widespread recovery in range condition, despite more than a decade of good rainfall seasons. An uncommon exception to this sad story is a group of sites located in the upper region of the Gascoyne catchment, where there has been almost continuous improvement over the same period.

This work also provides empirical evidence of a fundamental difference in the behaviour of surface water-flows in different catchment types. Using the Landscape Function Factor (LFF), there is conspicuous regional differentiation of sites located in exorheic catchments from those located in endorheic-arheic catchments. In general, sites located in the coastal draining exorheic catchments exhibit greater rates of soil erosion compared to sites located in the other internally draining catchment types; the different erosional regimes are probably related to the nature of the ultimate and local base-levels associated with each catchment type. This has important implications for the long-term management of the rangelands of Western Australia.

First and foremost, my sincere appreciation is extended to my two principal supervisors, Dr Brien (Ben) Norton, Associate Professor and Director, Centre for the Management of Arid Environments (CMAE), Curtin University of Technology and Dr Ian Watson, Research Officer, Department of Agriculture and Food Western Australia (DAFWA), and CMAE. I have benefited enormously from their extensive rangeland experience and knowledge, and their strong support, encouragement and belief in my ability to undertake this project. Ian kept me well nourished on a steady diet of journal papers and reports for which I also thank him. Dr Rob Corner (Senior Lecturer, Department of Spatial Sciences), an associate supervisor, provided valuable advice on spatial analysis, arranged for the supply of software and access to his department when required for which I thank him.

During the course of my studies, Ian and Ben endeavoured to deepen my rangeland experience. Ian involved me with other field projects in Western Australia, such as the vegetation re-assessments at Yerilla station (October 2004, March 2005) and Boolathana station (August 2005) and others, while Ben has involved me, from 2006, in the Curtin University - Omar al Mukhtar University, Libya collaboration which has enabled me to gain valuable experience in north African rangelands. For all of these opportunities, I am very grateful.

My interest in arid zone ecology began as a recently graduated geologist in central Queensland in the mid 1970s and was again piqued when working in the Great Sandy Desert of Western Australia in the early 1990s after many years sloshing about in the wet environments of Papua New Guinea, Indonesia, New Zealand and western Canada. However, my return to postgraduate study to undertake this doctorate was done with considerable trepidation. This was not because of an aversion to hard work, loss of salary or 'demotion' to mature-age student status, but because of the intellectual challenge of changing my scientific focus from mineral geoscience to arid zone ecology. I had no formal training in ecology or biology. The change in emphasis from abiotic to biotic phenomena required me to spend much of the first two years obtaining a basic level of botanical and ecological knowledge of water-limited ecosystems.

As it turned out, the change was facilitated by a number of factors. Apart from my long interest in deserts, these included a latent interest in jarrah forest and fire ecology which arose from my role as an EcoEducation officer, but most importantly, the very beneficial influence of many people. Indeed I was very fortunate to have several mentors who took me under their wing. Foremost is Dr Ken Tinley, the Father of geoecology in Western Australia who, with Dr Hugh Pringle, nurtured my understanding of the interaction of hydrogeomorphic processes and vegetation dynamics. It is with much fondness I remember lively and in-depth discussions with Ken and/or Hugh whilst perched on a breakaway scarp or standing in a canalised drainage. I also very much appreciate the experience of being a co-presenter with Hugh of the module Landscape Patterns and Processes, as part of the CMAE field course in Rangeland Ecology and Management for University of Western Australia undergraduate students at Cashmere Downs station in 2003 and 2004; it was not only the young students that learnt a great deal!

Whilst thanking Ken and Hugh, I also wish to acknowledge the other members of the now disbanded EMU (Ecosystem Management Understanding) team. Sally Black, Annabelle Bushell and P-J Waddell welcomed me into their social and intellectual circle, for which I am very appreciative. Jeff Richardson (Department of Environment and Conservation) was also an affiliate of that circle and through his witticism and self deprecation, definitely elevated the fun-factor of our get-togethers, whether in the field or elsewhere.

There are several other people who greatly assisted my apprenticeship in range science and the ways of the pastoral industry. Wayne Fletcher (Department of Agriculture and Food Western Australia, Northam) spent many weeks in the field in 2003, 2004 and 2005 in all regions from the Gascoyne to the Nullarbor teaching this new chum about the plants, data acquisition at monitoring sites, the grazing habits of different livestock, body condition scoring and numerous other facets of pastoralism. Wayne is well organised in the field, extremely knowledgeable and readily passes on his wisdom, for which I am very grateful. I also remember well, the many discussions regarding soil surface condition assessment. Working in the field with Wayne has been a highlight of my studies.

In addition to the field work, this project has involved manipulation of a very large amount of digital data, almost all sourced from the Western Australian Rangeland Monitoring System (WARMS). As manager of the WARMS database, Phil Thomas (Department of Agriculture and Food Western Australia, Perth) has been an integral part of this project and has applied his expert ability with MS Access to query, partition and extract data to my requirements. For this absolutely essential help, I sincerely thank Phil. In addition, Phil has an encyclopaedic knowledge of monitoring sites, plants and work done in the rangelands by DAFWA which has proved very useful on many occasions. In the same office as Phil, Damian Shepherd has cheerfully provided me with spatial data such as rivers, soils, land systems, vegetation and land tenure, essential for placing my work into context.

Jim Addison (Department of Agriculture and Food Western Australia, Kalgoorlie) has also been a tremendous help to me. He has an enormous depth of knowledge of livestock and practical rangeland experience which, when one is tapping into it, is usually delivered with extra dry humour. Jim is also a valuable source of information on early monitoring techniques and together with David Wilcox (formerly Department of Agriculture Western Australia), the Father of range monitoring in Western Australia, have provided me with personal accounts of their monitoring work, for which I am very grateful.

Greg Brennan, former Kalgoorlie–Nullarbor District Manager made me feel very welcome in the Kalgoorlie Office of the Department of Agriculture and Food Western Australia when I first moved to the co-located Centre for the Management of Arid

Environments (CMAE) in 2002. Together with his wife Fiona, their warm hospitality made my early time in Kalgoorlie much more pleasant and sociable. Greg opened my eyes to two things: one, the importance of socioecology in the rangelands and two, the understated role of perennial grasses as forage in the shrublands. Thanks also to Corina Hitchcock, formerly CMAE, who patiently and competently guided me through the 'hoops' and 'hurdles' of the Muresk Institute and Curtin University administrative procedures.

Another person who has had a strong influence on me through numerous publications and in the field is Dr Alec Holm (formerly DAFWA). He was the principal designer and champion of WARMS in the 1980s and 90s. Alec injects a healthy level of scientific scepticism, despite (or perhaps because of) his vast experience in rangelands, for which I am very appreciative.

I must also mention again Peter-Jon Waddell who very kindly allowed me to share his house in Kalgoorlie from 2003 to October 2005, after which he changed roles within the Department of Agriculture and Food and shifted to Perth; was my cooking that bad PJ? He and I had numerous interesting discussions about the rangelands. I particularly appreciated (and still do) his keen field observations and interest in the geological and geomorphological aspects of range science.

Following PJ's departure from Kalgoorlie, Ben Norton then very kindly provided me with a room and use of his house when I needed to be in Kalgoorlie, albeit less frequently in the latter stage of my studies. I very much enjoyed Ben's conviviality and good cooking, particularly his Moroccan tagine dishes, and watching rugby matches together. Thank you very much Ben for all the help you have given me over the years.

Another person who I feel very privileged to know is Angas Hopkins (Department of Environment and Conservation) who, through his infectious enthusiasm, quirky humour and personable interest, continues to boost my confidence and enthusiasm for the rangelands and life in general. Angas has also provided me with challenging intellectual distractions from time-to-time including substantial geological involvement in a proposal for World Heritage Listing. Good luck with your PhD Angas.

I wish also to thank David McQuie and his family, including his Dad Murray, for their outstanding hospitality and support during field trips to Cashmere Downs–Bulga Downs station.

My many good friends and colleagues, past and present in the EcoEducation team (Department of Environment and Conservation) also deserve credit for their strong support and interest, and for coping with my extended absences over the last three years.

I owe special thanks to John Lang (Curtin University postgraduate student in the Department of Spatial Sciences), who very ably assisted me with expert, patient and friendly guidance through the intricacies of ArcGIS spatial analysis. It is this recent work with John which has enabled me to bring to very pleasing fruition, five years of endeavour.

Finally, my gratitude to all members of my family is immeasurable. To Lucinda, my Mum and Dad, sister Lesleigh and brother Greg, thank you for the encouragement to keep going when it got tough. This body of work is a tribute to your support.

This work was supported by an Australian Research Council (ARC) Linkage Project scholarship (LP 0235349) from 2002 to 2005 and project research funds contributed by industry partner, the Department of Agriculture and Food Western Australia (DAFWA), for which I am very appreciative. I would also like to sincerely thank DAFWA for the considerable support provided to me, both in the field and by allowing ready access to staff for assistance and information. My thanks are extended to Dr Ed Barrett-Lennard (DAFWA), as the ARC grant Chief Investigator, for his support. Curtin University is also sincerely thanked for its financial support of my attendance at the Australian Rangeland Society 13th Biennial Conference in Alice Springs, July 2004, and for general support during my studies.

In conclusion, I feel very privileged to have been able to undertake such an enlightening journey of discovery. It has enhanced both my scientific understanding of arid landscapes and my appreciation, indeed admiration of those people living in this environment. To all the people who have participated in my journey, in small or large measure, named above or not, I extend my sincere gratitude. This project was conceived and made possible primarily by Dr Ian Watson who saw the need for research into ways to extract more information from long-term monitoring data; I trust his vision has been satisfied at least in part.

Peter J Russell
October 2007.

TABLE OF CONTENTS

Chapter **Page**

TABLE OF CONTENTS

Chapter **Page**

LIST OF FIGURES

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES

LIST OF PLATES

1 Introduction

Chapter 1: Introduction

In the context of pastoral management of rangeland natural resources, long term change in soil and vegetation attributes in response to climatic conditions, herbivore grazing, fire and other influences is described as change in range condition, or range trend if assessed over time (Holm, Burnside & Mitchell 1987). Whilst acknowledging the valuable but necessarily subjective component of much condition information, Burnside and Faithfull state (1993 p.247), that "the acquisition and interpretation of objective data is intended to make the determination of [range trend] clear and unambiguous." In a similar discussion, Wilcox and Burnside (1994) also describe the factors which forced rangeland administrators in Western Australia in the 1980s to recognise the potential value of objective descriptions of resource condition.

However, due to a number of factors, land managers and pastoralists in the Western Australian rangelands (Figure 1.1) have not yet been provided with an appropriate, comprehensive and integrated ecologically-based information and decision framework. Inhibiting factors include the difficulty of unravelling the complex nature of observed and measured changes and their associated causal relationships at monitoring sites and elsewhere in the landscape, and translating the information into land management and sustainable grazing management decisions. Whilst recent developments such as Rainman© software to analyse historic rainfall data, decision-support methods such as Bestprac© and marked improvement in landscape ecological knowledge facilitated by the Ecosystem Management Understanding programme (Pringle *et al.* 2003) (unfortunately, discontinued from end 2005) are very useful to pastoralists, the major information shortcoming still stands and has been recognised previously by many people, as described by Wilcox (1988) and Burnside and Faithfull (1993). This shortcoming includes the paucity of an objective measure of range condition and trend, and is one of the relatively recent significant factors, along with the historic legacy of inappropriate European strategies of

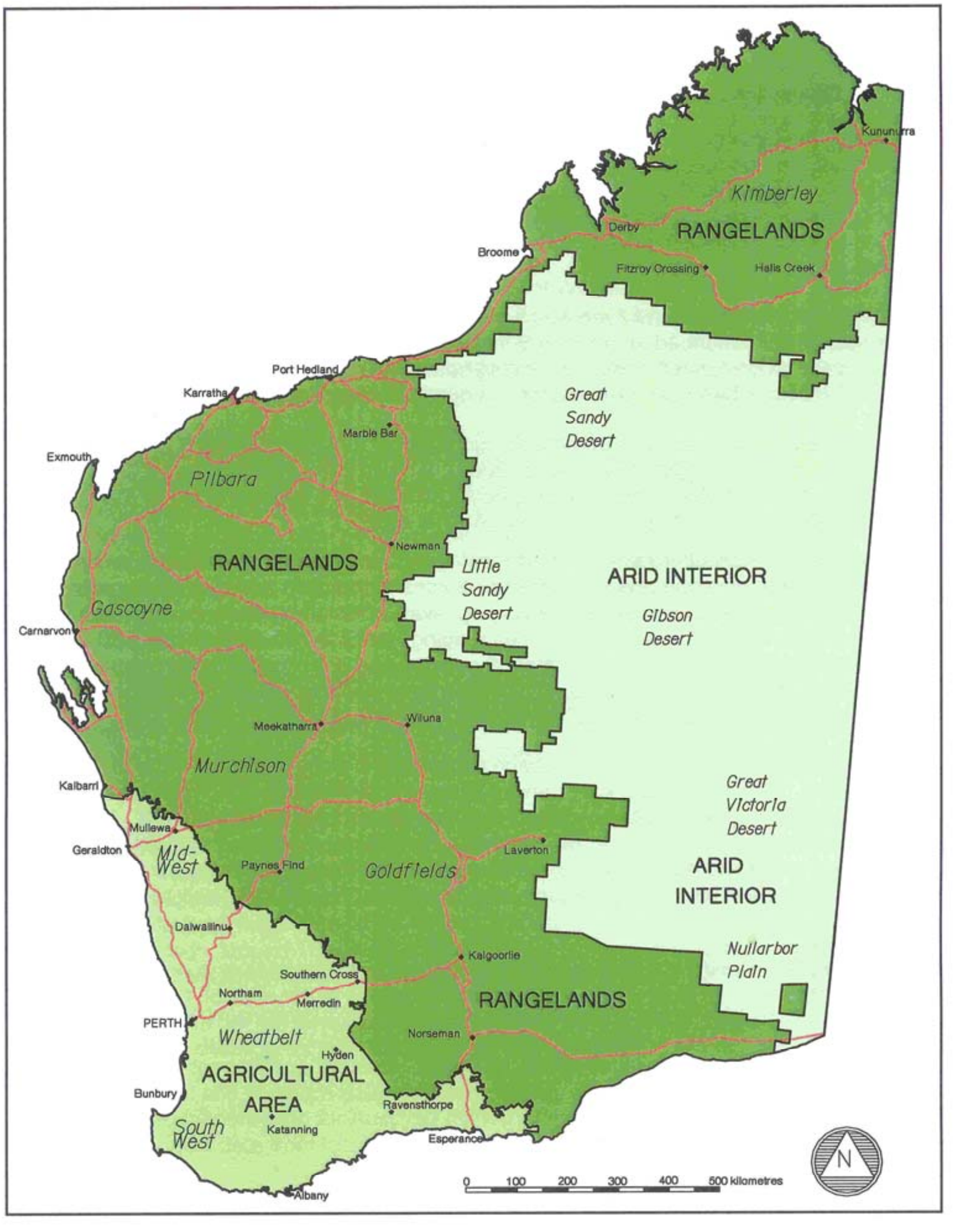


Figure 1.1 Extent of pastoral rangelands and location of regions in Western Australia (from Tille 2006).

continuous grazing and set stock numbers since pastoralism began in Western Australia (WA) more than a century ago (see Section 3.2 for additional historical information), which has contributed to rangeland degradation. It is the development of an objective, quantifiable measure of range condition that is the subject of the research described here.

Another significant degradation factor recognised by Wilcox (1988) is that responsibility for grazing management decisions has at various times and through various regulatory mechanisms been removed from the pastoralist themselves. For example, the imposition of minimum stocking rates by the government, irrespective of seasonal conditions meant that even environmentally aware and caring pastoralists were not allowed to practice ecologically benign grazing. Wilcox (1988) in his discussion of 'fair use' and 'fair go', eloquently expands on this and other aspects of pastoral land management, providing reasoned arguments for the legacy of rangeland degradation which applied in 1988, and unfortunately, still largely apply in 2007.

It is hoped that the research described herein is viewed as a positive step towards the institutional process of providing pastoralists, rangeland managers, administrators and others with a means to more objectively assess 'fair use' – that is, a tool which incorporates defined ecological relationships between monitoring site soil and vegetation attributes and derived quantitative range condition and trend indices. This work is also applicable in the broader context of the societal trend towards multiple use of rangelands and the involvement of other scientific and socio-economic disciplines of investigation (the "shift in the multi-disciplinary environment" of Wilcox and Burnside (1994, p.301)). It should at least partially fill a gap in regional analyses which has in the past, been a constraint to effective implementation of new models of land use decision making that try to or should incorporate regional-scale ecological criteria, enterprise-scale economic criteria and community-scale social criteria (Wilcox & Burnside 1994). This research work has relied on a long-term monitoring system and through its use demonstrates the very high value of maintaining such a system, and indeed, it could be argued on ecological or biodiversity grounds, that this monitoring system should be expanded and augmented to fulfil a wider ecological monitoring role.

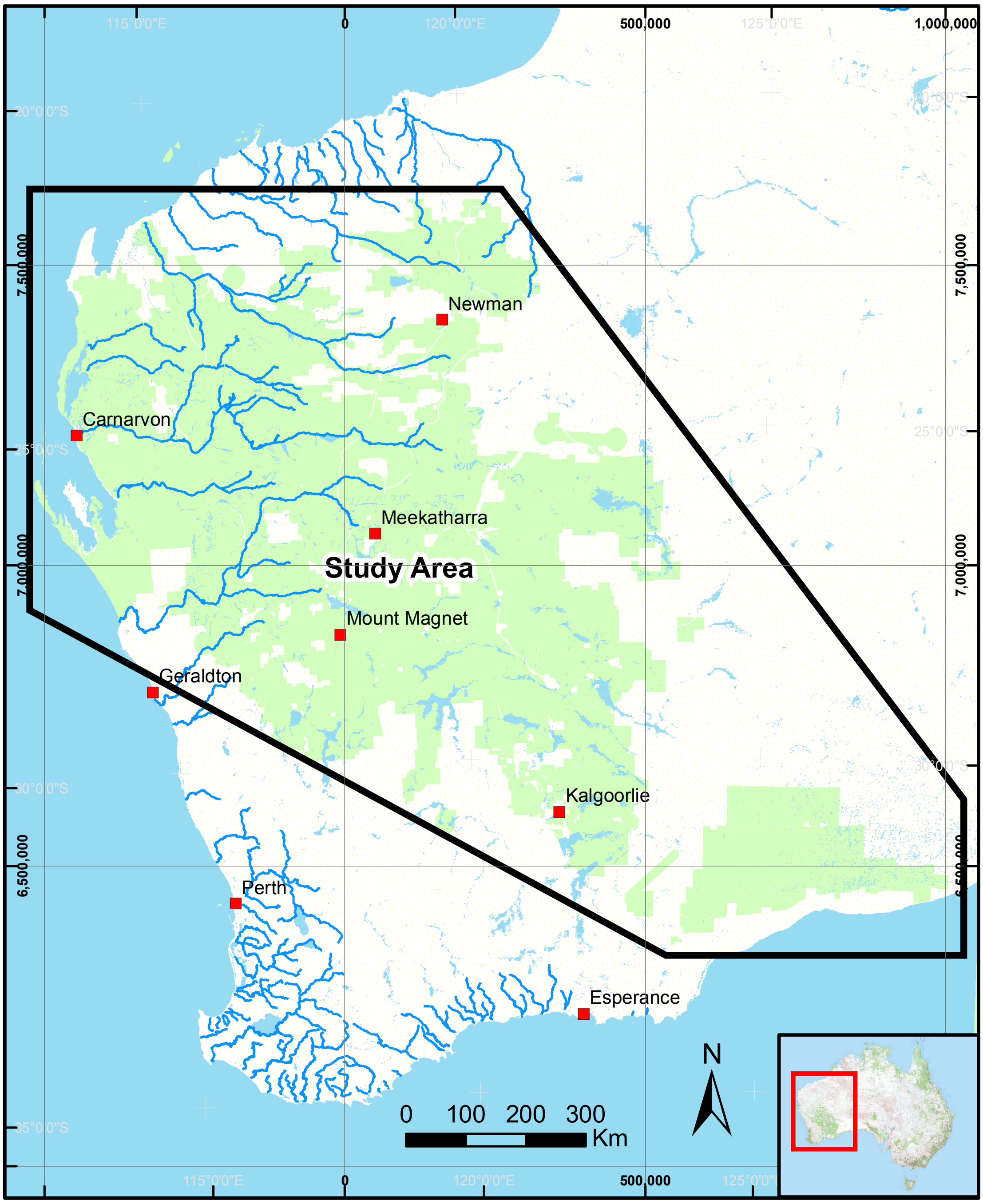
1.1 Project Background and Significance

This project was instigated by Dr Ian Watson, Research Officer, Department of Agriculture (now Agriculture and Food) Western Australia (DAFWA) in 2002. He recognised that the Western Australian Rangeland Monitoring System (WARMS) had accumulated a vast amount of ecological data on the rangelands of Western Australia. Data collection protocol has remained essentially unchanged since 1992, therefore, a comprehensive body of reasonably coherent data spanning more than a decade was available, from which temporal and spatial patterns of range condition might start to emerge through appropriate analysis. It was also recognised that in achieving this analysis, a number of ‘higher level’ objectives could also be met, as outlined below.

Several international conventions (e.g. *Convention on Biological Diversity*) and national strategies (e.g. *National Principles and Guidelines for Rangeland Management; National Strategy for Conservation of Australia's Biological Diversity*) stress the need to develop and implement monitoring programmes to track change in the environmental health of Australia's natural biological resources. The Commonwealth (Alexander 1996) and the states have begun regular *State of the Environment (SoE)* reporting (Anon. 2006a).

The research has, in relation to the rangelands, substantially addressed the statutory demands and reporting requirements for more spatially and temporally explicit information on range condition, required by the various International, National and State environmental conventions and strategies mentioned above.

Western Australian Rangeland Monitoring System (WARMS)



Legend

- Towns
- Major Rivers
- Lakes and Salt Lakes
- Study Area

Coordinate System: MGA 94 Zone 51

Extent of Pastoral Leases in the Southern Arid Shrublands and Location of Study Area

Peter Russell

12 September 2007

Figure 1.2

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

C:\SRCGIS\MapDocuments\WARMS_LocationOfStudyArea_MGAZ51_20070911.mxd

The Northern Territory and the states of South Australia, Queensland, New South Wales and Western Australia are actively engaged in rangeland monitoring designed to meet their own strategic needs. In Western Australia, WARMS is seen as an important potential component in the development of Environmental Management Systems for pastoralists and the wider pastoral industry in helping to demonstrate the industry's environmental credentials. Progress in this area, although slow to date, is necessary to ensure that individual and industry stewardship of the natural resources is ecologically responsible, productivity is sustainable and market access, through accredited 'green' and quality assurance schemes, is maintained.

The primary significance of this research is that quantitative spatial and temporal assessment of range condition change over the last two decades in the arid pastoral shrub-dominated rangelands of WA has been achieved. The type and scale of analysis used herein has not been done before in WA. Although statistical, non-map based analyses for specific regions within the shrublands (and grasslands) of WA using a limited number of measured attributes such as total plant density are presently done for the WA Pastoral Lands Board for example, no previous work has mapped the entire pastoral shrubland region using an integrated multi-criteria suite of ecological indicators derived from the WARMS data. This work could be used to inform policy development and to support current pastoral and other land management decisions at regional scales.

Judgements about whether changes have been positive or negative, using a transparent set of ecological attributes can now be made (Ludwig *et al.* 1997). For a specified land use, values could be applied in an assessment. For example, an increase in woody perennial plants may be positive when viewed from a carbon sequestration perspective, but negative from a pastoral production or biodiversity conservation perspective. Therefore, this work could also be a useful resource for

Natural Resource Management (NRM) bodies and communities working in the southern rangelands of WA.

1.2 Research Objective, Outcomes and Applications

The principal objective of this project is to produce a regional-scale assessment of changes in the ecological health or range condition at WARMS sites in the arid shrublands of Western Australia over the last two decades. The extent of the pastoral shrublands, also known as the southern rangelands and location of the study area are shown in Figure 1.2.

The project utilised data from the WARMS database (see Chapter 3 for a review of WARMS) and due to inherent limitations in the data, the ecological health assessment does not constitute a comprehensive biodiversity assessment.

Outcomes achieved include:

- A quantitative index of ecological health (range condition), developed from a suite of ecological attributes, collectively encompassing structural, compositional and functional elements of ecological integrity.
- Maps showing the changes in ecological health (range condition) through time and space.

There are several uses or applications for the results of this research. These include, first, providing pastoralists with regional contextual-information on range condition and trend which may be then incorporated into grazing management strategies. In Wilcox's jargon, this assessment would constitute a relatively objective measure of 'fair use' (Wilcox 1988). A second application is the provision of more spatially and temporally explicit management and reporting of rangeland health by government, including for SoE reporting. Another application includes the identification of areas requiring remediation or particular land management strategies, although there are limitations to the sensitivity of WARMS monitoring (and derived indices) to the early detection of degradation in certain parts of the landscape; this aspect is discussed in Chapter 3 (Section 3.5).

1.3 Overview of Data and Research Methods

The assessment covers an area of approximately 760,000km^2, stretching southeast from the Pilbara region through the Gascoyne-Murchison and Goldfields to the Nullarbor region on the Great Australian Bight (Figure 1.2). WARMS is designed to provide data and information for assessing regional and long-term changes in rangeland ecological condition.

WARMS consists of two principal parts; (1) numerous permanent field monitoring sites and (2) a large relational database. By the end of 2006, there were 980 WARMS sites located on 377 pastoral leases (stations) in the southern rangelands of Western Australia. Average lease size is 202,190ha and the largest is 714,670ha. The total area occupied by leases (pastoral and leases converted to conservation estate) is approximately 76,250,000ha. WARMS sites are at an average density of 2.6 sites per lease or 1 site per 77,780ha of pastoral rangeland. Field recorded metrics include 11 soil surface parameters and four plant parameters (location on belt-transect, species, height and maximum canopy extent). The field data collection protocol has remained essentially unchanged since 1992 and new field data are captured at each site on a 5 year cycle. This is the most extensive census-based quantitative, ground-based rangeland monitoring system in Australia, and is larger than any single quantitative monitoring system in the rangelands of north America. For example, by the end of 2006, over 550,000 plant height measurements were recorded.

This range condition assessment is based on a suite of soil and vegetation indices derived from the WARMS transect field metrics. MS Access queries were used to extract and partition field metrics and to calculate the indices. Seven basic indices were derived and algorithmically combined into three higher-order indices, one for each of three aspects of ecological integrity: composition, function and structure. The three indices were then combined into an overall index of ecological health called the Shrubland Range Condition (SRC) Index. In addition, the indices have been assigned to particular time-slices based on the field acquisition date of their component metrics, allowing the calculation of change through time. The combination of a hierarchical index framework, the use of time-slices and GIS mapping techniques has provided a potent analysis platform for the elucidation of spatial and temporal change in rangeland ecological integrity or health at WARMS sites. The nature of change in the SRC Index and its sub-indices, particularly relative changes in the landscape function, vegetation structure and vegetation composition indices have enabled possible causes of change to be inferred at many sites, based on ecological first-principles.

1.4 Rangeland Ecological Health

This project is concerned with ascertaining regional-scale trends or changes that have occurred in the ecological health of the arid shrublands of Western Australia over the last two decades. Consideration of what is meant by ecological health is discussed including a consideration of related terms such as biodiversity, conservation values and ecological sustainability.

The discussion is restricted to consideration of biophysical or ecological aspects, rather than dealing with the much wider, though no less important aspects of social and economic components of rangeland management and activities.

As yet, there is no universally accepted definition of ‘health’ or ‘condition’ (the terms are essentially interchangeable) when applied in an ecological or biophysical sense to an environment. However, they have widespread use and appeal as holistic or generic terms, implying to most people, aspects of biodiversity and ecosystem functionality. Thus, an environment in 'good health or condition' implies an acceptable level of biodiversity and/or sustainability, and, by analogy with human health, a relatively high level of resistance to detrimental stresses. Good 'health' or 'condition' does not necessarily mean that an environment is in a pristine natural state.

For this project, health or condition is described as the state of an ecosystem which reflects its intrinsic ability to sustain a complete range of ecosystem functions and life-support for its biotic components. Ecosystem functions include natural biogeochemical and physical processes, and can be considered at a variety of spatial (landscape, vegetation assemblage, patch) and temporal scales. It could be inferred therefore, that a healthy system is better able to withstand detrimental impacts than an unhealthy system. For example, a healthy waterway, as described by Bennett *et al.* (2002), is free from distress, more resilient and less at risk from disturbances. The nature of the disturbances is, however, an important aspect in determining the response of a system, as is the concept of acceptable change.

For systems that have suffered accelerated change, induced either anthropogenically or naturally, it is important to consider whether 'health' or 'condition' also implies compositional integrity or the 'closeness' to which a system is to its previous unaltered 'natural' state. Hypothetically, for example, in the rangelands, an area may have been subject to prolonged moderate-pressure grazing and over that time, a particular palatable plant eliminated. Recruitment of slightly less palatable plants has occurred and there have been no apparent deleterious affects on any other plant species as a result of the loss of the one plant. Thus, the system might still be described as 'healthy' despite the loss of one species, since biophysical function is maintaining support for all other species. However, this example fails to highlight the fundamental fact that within an ecosystem, everything is interconnected and therefore other changes may have been induced but are not yet manifest. The role of key species is also an important consideration. This aspect is discussed in relation to the development of one of the vegetation structure indices in Chapter 4 (Section 4.6.2).

1.4.1 Conservation Value and Protection

'Conservation value' is a value which people place on natural and cultural heritage assets (Bennett *et al.* 2002). Other values such as recreation, visual amenity, scientific interest, productivity and human health, are implicitly included because they are supported by properly functioning ecosystems, that is, the ecosystem services. The definition of 'conservation' used for this project is that provided by the Australian Heritage Commission (AHC 1996); conservation includes all the processes and actions in looking after a place in order to retain its natural significance – always includes protection, maintenance and monitoring.

In essence, the 'conservation value' that might be placed on an asset is a 'protection value' or a measure of individual, community and government commitment to managing that asset. The Australian Heritage Commission defines protection as taking care of a place by maintenance and by managing impacts to ensure that natural significance is retained (AHC 1996). Importantly, the stakeholder's desire to protect a particular place is strongly influenced by a 'champion of the cause' and available scientific information; this information needs to be objective, readily accessible and understandable by non-specialists.

The natural parts of any environment may also be considered as 'ecological assets' on which an 'ecological value' might be placed. Ecological value, as defined by Bennett *et al.* (2002 p.35), is the natural significance of ecosystem structure and functions, expressed in terms of their quality, rarity and diversity – significance arising from individual biological, physical or chemical features, or a combination of features.

1.4.2 Ecological Sustainability

Unlike the term ‘health’ (or ‘condition’) which has a spectrum of states from ‘excellent’ through ‘poor’ to ‘moribund’ or ‘dead’, an ecosystem is either sustainable or not sustainable, over a specified timeframe. Clearly, for example, an ecosystem that is currently in fair but declining health is viable over some period, but is not viable over a longer period. Therefore, it is this author’s firm view that a statement of the timeframe should qualify use of the term ‘sustainable’. The challenge for rangeland managers, scientists and for this project is clear. It is to measure the shift in ecological health of ecosystems subject to accelerated natural or, more usually, anthropogenically-induced perturbations and to establish sustainable thresholds for specified timeframes.

In consideration of a definition of ecological sustainability for use in this project, the following information on concepts is largely taken from Bennett *et al*. (2002 p.29) Several concepts, summarised below, have been advanced by various organisations. Each has merit, depending on its application. The concepts include:

- ‘Intergenerational equity’ – maintaining natural ecosystems and resources that have no known substitutes, the loss of which would be detrimental for future generations.
- ‘Ecological integrity’ – maintaining the composition, structure and processes of an ecological system, and a variation of the same concept,
- ‘Ecological integrity’ – the protection of native biodiversity, essential ecological processes, and life support systems.
- ‘Natural extinction rate’ – the maintenance of life support systems and the achievement of a ‘natural’ extinction rate.
- ‘Natural capital’ – maintaining and enhancing natural capital, avoiding overexploitation of renewable resources, and minimising waste.

These concepts, although worded differently, do in fact emphasise essentially the same aspect, that is, the maintenance of properly functioning ecosystems, but only two descriptions include any reference to time. It may be implied or ‘generally understood’ in the other concepts that ‘sustainability’ is for some unspecified but long period of time.

The definition of ecological sustainability espoused by Bennett *et al*. (2002 p.35) is “the ability of ecosystems to maintain their natural structural and functional integrity in response to perturbations.” This author sees scientific merit in this definition, in so far as specific ecological attributes (structure and function) are included, however, again, there is no timeframe qualification. For this project, it is proposed to use the above definition, slightly modified and with an added timeframe qualification that takes into account ecological (not human) timescales. Thus, here, ecological sustainability is defined as the ability of an ecosystem to maintain its structural and functional integrity over natural ecological periods in response to human-induced perturbations. Ecosystem composition is specifically not included because the loss or replacement of non-critical or ‘non-keystone’ species may not change the long-term sustainability of an ecosystem. Species loss however, is a loss of biodiversity and a downgrading of ecosystem integrity. Composition is included as an element in the multi-criteria index developed in the research reported here.

Human-induced perturbation is specified because it is this type of stress that causes unnaturally accelerated change. It is understood that under completely natural conditions, no ecosystem will remain forever unchanged, due to changes in both shorter-term drivers and the fundamental long-term, interactive geological and climatic drivers of ecosystems. However, the difficulty in practical application of the above definition is in knowing the nature and extent of natural variations or flux over ecological periods, given that many processes operate over considerably longer periods than human timeframes.

1.4.3 Biodiversity

Biodiversity, or to be more inclusive, biodiversity and geodiversity, are terms which together, refer to all components of diversity, namely, composition, structure and function (process), and these can be applied at scales from the level of genes to regional or whole-of-landscape level. Ward *et al*. (1999) identified a hierarchical suite of indicators for composition, structure and function for use in waterway biodiversity assessment (see Table 1.1) and which are also essentially applicable, with some modification, in other environments such as the arid shrublands.

Table 1.1 Indicators of diversity (from Ward *et al.* 1999)

HIERARCHICAL LEVEL OF DIVERSITY	Composition	Structure	Function
Genetic	Allelomorphism	Heterozygosity Polymorphism	Gene flow Genetic drift Mutation rate
Population / Species	Occurrence frequency Relative abundance	Microhabitat structure, Ecotones	Life history, Metapopulation dynamics, Adaptations
Community / Ecosystem	No species per habitat[1] (α) No species turnover between habitats[2] (β)	Habitat heterogeneity Ecotones	Water, energy, nutrient transfers, Patch dynamics Succession Connectivity
Landscape	No species in landscape / region[3] (γ)	Geomorphic patterns Large-scale environmental gradients Ecotones	Disturbance regimes Hydrological processes Connectivity

Notes:

1. Alpha diversity (α): the number of species per habitat.
2. Beta diversity (β): reciprocal of the mean number of habitats per species; essentially a measure of species turnover between habitats.
3. Gamma diversity (γ): total number of species in a region.

As stated by Bennett *et al*. (2002 p.30), when assessing ecological value, a low diversity does not necessarily imply a lesser value, since some ecosystems have intrinsically low diversity.

2 Overview of Arid Landscapes Patterns and Processes

Chapter 2: Overview Of Arid Zone Patterns and Processes

"Life on Earth may be expensive but it includes an annual free trip around the Sun"
Anon., Sydney 1995

2.1 Introduction

The purpose of this chapter is to provide background ecological information for subsequent chapters, particularly Chapters 4 and 5 which deal with (respectively) the development of indicators of ecological health or range condition used in this study and their spatiotemporal patterns in the southern rangelands of Western Australia.

The scope of this research project, particularly with its emphasis on establishing spatiotemporal patterns of range condition, marks it as a study in landscape ecology or, more specifically, arid landscape ecology. The term landscape ecology, coined by the German biogeographer Carl Troll in the late 1930s, combines "the spatial horizontal approach of geographers and the functional vertical approach of the ecologists" (Farina 2006, p.1), and has evolved toward a comprehensive science of landscape. It is now a very broad discipline encompassing the study of complex ecological systems, with particular emphasis on spatial patterns and processes involving soil, vegetation, fauna and human beings (Farina 2006). In a sense, it is similar to the long-established discipline of anthropogeography, the study of the relationship of human communities with their natural environment. For further discussion of the incorporation of paradigmatic and theoretical frameworks such as nested hierarchy, percolation theory, the source - sink paradigm, metapopulation theory and others into landscape ecological studies, the interested reader is referred to Farina (2006) and references cited therein.

It is interesting to note, however, in contrast to the amalgamation of multiple physical, biological and social science disciplines into the ‘new’ science of landscape ecology, is the emergence or development of new subdisciplines. The subdiscipline or term ‘ecohydrology’ is being increasingly used to encompass studies of the relationships between hydrological aspects such as patterns of soil moisture and ecological patterns of vegetation, plant physiological processes and nutrient cycles, etc; see D’Odorico & Porporato (2006) for a comprehensive treatment of ecohydrological aspects. Where the emphasis is on geomorphic relationships with ecological patterns and processes, the term ‘geoecology’ may be preferred and where the emphasis is on plant types or morphology in relation to regolith or underlying bedrock, the term ‘geobotany’ may be used.

2.2 Overview of Arid Zone Ecosystem Drivers

2.2.1 Introduction to Landscape Processes

The natural Earth Surface System drivers affecting the landscape interact over a large range of spatial and temporal scales. The fundamental or ultimate drivers are the geological and climatic processes operating continuously at global and continental scales. The processes include tectonic events such as continental drift, collision and break-up, and associated interactive oceanic and atmospheric circulation patterns. These influence how and where the hydrological cycle operates, through the development of surface topography (orographic and adiabatic processes, drainage patterns and flow regimes), oceanic circulation patterns and polar cooling (circum-polar circulation, albedo effect), coastal (maritime) climatic influences and topographic denudation (erosion/sediment flux).

In other words, climatic and geological processes interact at various spatial and temporal scales to control terrestrial weathering, erosion and deposition of sediment on the Earth’s surface; this is the physical evolution of the land surface through geological (rock), geomorphic (surface) and hydrological (water) processes. The flux of water, sediment and contained nutrients (e.g. phosphorous and nitrogen) derived from the weathering of rock, control the take-up by plants, and therefore, biomass production.

The manner in which drainage catchments behave, particularly expressed through soil-water balance relations, reflects the net result of these processes, thereby providing a link or understanding framework between the climatic and geological drivers and the local/regional landscape. Holistic or integrated catchment management recognises that changes or perturbations move through the physical and ecological space of the catchment, causing the flow-on and feedback effects between adjacent or related habitats, that is, the interdependence of ecosystems. The interdependence aspect is very important to understand and be cognisant of in natural resource management.

The relative importance of the climatic, topographic and geological drivers depends on the scale at which the landscape is being considered. For the southern rangelands of Western Australia, the regional climatic, geological and physiographic settings are outlined below.

2.2.2 Biophysical Characteristics of Drylands

Drylands occupy slightly more than 40% of the Earth's land surface and are home to about 20% of the global population (Reynolds & Stafford Smith 2002, Chapter 21). Based on human land use, drylands may be categorised as:

i. Irrigated cropland,
ii. Rain-fed cropland, or
iii. Rangeland.

According to UNEP 1997 (cited by Reynolds & Stafford Smith 2002) of the World's drylands, only 3% comprise irrigated cropland, 9% is rain-fed cropland and the remainder (88%) is rangeland where the grazing of managed livestock on native vegetation is the principal agricultural activity.

But given that about 80% of the World's population does not live here, why is a strong interest in drylands being shown by organisations as diverse as the United Nations, the World Bank, various state and private agricultural enterprises, mineral and petroleum resource companies, and numerous universities and other research centres? The strong interest is engendered by, first, the very high economic and social importance of most dryland regions of the World; and, second, a desire to improve processed-based understanding of hydrosphere - biosphere interactions in water-limited ecosystems, in response to different climatic and land use-induced hydrological conditions. Interest is heightened because of the likelihood of adverse changes in many drylands arising from anthropogenically accelerated global climate change.

Whilst the socioeconomic aspects are obviously important, their detailed consideration is beyond the scope of this study; only passing comment is made in later sections in relation to desertification and the pastoral industry in Western Australia. The following discussion is focussed on the characteristics of drylands and their ecosystem drivers.

Drylands are characterised by frequent, persistent or chronic water limitation and sensitivity to daily, seasonal and decadal perturbations in water availability. The variability operates across a range of spatial and temporal scales; for example, interannual rainfall variability may be as large as 50 to 70%, with extended dry periods persisting for one, two or more years. High rainfall variability is characteristic of most drylands and is indicative of frequent drought conditions.

Variations in annual water budget are dependent on the natural variations of global-scale climatic and related systems.

Regional patterns of vegetation (and domestic crops) are strongly influenced by climatic conditions. Simply, for example, forests occur in humid regions with sufficient moisture throughout the year whereas grasslands and woody savannas occur in subhumid regions with distinct dry and wet seasons. Vegetation in the semiarid regions is usually highly patterned, consisting of various mixtures of grasses, shrubs and small trees. This patterning characteristic is utilised in Chapters 4 and 5 as one of several measures of landscape functional health.

A Comment on Scale

Scale, both absolute and relative, is a fundamental concept in ecology (Farina 2006). In considering ecological processes, it is clear that abiotic and biotic interactions operate at various temporal and spatial scales. Spatially, these range from the very large, broad scale, such as global extent, to the very small scale with very localised or limited extent. Temporally, processes also operate over a similarly wide range from millions of years ('geological time') to very short time intervals. Thus, in ecological usage, "particularly [in] landscape ecology, scale refers to the spatial or temporal dimensions at which an organism or a pattern or process are recognisable" (Farina 2006, p.88). An important aspect is that large-scale patterns may be determined by large-scale processes or by the collective forcing of smaller-scale processes, each acting either independently or dependently.

Note that usage of the term 'scale' in this context is different from cartographic usage where, for example, a large-scale map (e.g. 1:500) covers an area of very limited extent compared to a small-scale map (e.g. 1:5 million) which covers an extensive area.

The above discussion pertains to the perception of 'extent' in scale, that is, the spatial area or temporal duration of a particular process or pattern. However, 'grain' is the second component of scale, and pertains to the minimum dimension or finest level of observation or resolution possible with a given data set at which the pattern or process is recognisable in its entirety or as an identifiable part of an entity.

Comment on Hierarchical Organisation of Ecosystems

Farina (2006) provides a succinct discussion of this topic and urges us to recognise the scaled hierarchical arrangement of ecological systems as a necessary framework for understanding relationships between processes or drivers and patterns.

An important contribution to this subject is provided by two Western Australian rangeland ecologists, Hugh Pringle and Ken Tinley (Tinley 1982; Tinley 1991; Pringle & Tinley 2003; Pringle, Watson & Tinley 2006). The essence of their work is that ecological degradation in the rangelands is manifest as the loss of critical water-ponding or low-energy surfaces at catchment to vegetation patch scales. The catchment is the fundamental geoecological unit. They describe degradation in terms of an acceleration of the erosional processes of base-level incision, drainage network intensification and increased through-flow (canalisation) of surface waters. This cascading, self-perpetuating nested set of processes leads to landscape desiccation, reduced rainfall-use efficiency, vegetation homogenisation and biological depauperisation. These processes can be placed in a hierarchy of salience, operating at different temporal and spatial scales. Importantly, this means that local degradation dynamics are able to be placed within much higher-order, broad or catchment-scale dysfunction regimes (Pringle, Watson & Tinley 2006).

2.2.3 Ecological Models for Australian Drylands

Over the last two decades, there have been several attempts to develop broad-scale or overarching ecological models applicable to Australian arid and semi-arid zones. The models by Westoby (1979/80); Stafford Smith and Morton (1990) and Ludwig *et al.* (1997) are briefly described below, following an overview of Clementsian range succession. These models provide a framework which helps us to understand the functional relationships between the biotic and abiotic components. By better understanding the relationships, we are then in a better position to elucidate the causes of environmental change including degradation. Indeed, Austin (2002) maintains that three types of model are required to properly and effectively investigate the drivers of change; the models are:

- Ecological model – a framework of key environmental drivers including feedback loops.
- Data model – a data measurement framework to represent key environmental responses and drivers.
- Statistical model – to determine the degree of association between response and driver variables.

Whilst it is not this author's intention to provide a critical review or examination of ecological modelling theory and practice, it is worth noting that the above model structure is a useful framework within which this project can be considered.

In regard to the ecological model, it is important to note that this project is not dependent on any particular model of rangeland or vegetation dynamics. It does, however, incorporate some elements or aspects of several models developed for Australian rangelands, described in more detail below, either as important underlying assumptions in the type of data collected (the data model) or in the way data are interpreted (the statistical model). Details of the data model (ecological index framework), based in part on aspects of the last three models described below, are provided in Chapter 4, and the statistical or interpretive model is described in Chapter 6.

2.2.3.1 Classical or Clementsian Range Succession Model

This is not an Australian model but its science has underpinned rangeland management practices in parts of the World's drylands since it was developed in the US between 1915 and 1960. Its ongoing influence in Western Australian shrubland studies is however, minimal.

The underlying precept in succession theory is that vegetation can be in equilibrium with climatic and soil conditions, and with disturbances such as grazing (Clements 1916, 1938; Tansley 1935; Dyksterhuis 1949 cited in Westoby (1979/80)).

The successional model of vegetation change holds that vegetation is always in a stable equilibrium or seral stage with any particular stocking rate. The equilibrium condition is the result of two steadily applied and directly opposed forces, one being grazing pressure and the other being the intrinsic tendency of vegetation to progress to a climax condition; or, if not yet realised, a potential climax. The two important underlying assumptions for predicting vegetation response to grazing in this model are:

i. Vegetation response is continuous, direct and rapid, and
ii. Response is to two opposite, potentially balanced forces: these are interspecific competition and perturbation (grazing or drought); for example, overgrazed vegetation resembles either more xeric vegetation or drought-affected vegetation.

Application of these assumptions leads to the use of stocking rate (adjusted up or down) to modify vegetation towards desirable assemblages. For example, a reduced stocking rate could be used to change an assemblage dominated by annuals to one dominated by perennial grasses or shrubs. The ungrazed climax is usually assumed to contain the most palatable plants and to be the most productive (Westoby 1979/80). Thus rangeland managers and ecologists who utilise this model are concerned with classifying vegetation into climax types, establishing or defining pre-climax seral or equilibrium stages for each climax type under different stocking rates, and calculating the economic return for each scenario.

Whilst intuitively appealing and with sound practical application in the mixed-grass and short-grass prairies of north America, it lacks robust application in many arid zone vegetation assemblages such as the water-limited Australian shrublands and woodlands. The model-confounding or contradictory vegetation responses in the latter environments are due, at least in part, to the discontinuous and irregular vegetation response trajectories compared to the more continuous responses under low-variability climatic conditions of American prairies. Furthermore, vegetation responses to grazing and other perturbations in Australian shrublands do not follow the seral stages predicted by the Clementsian succession model. Put simply, models relying on equilibrium relationships are not applicable to arid environments with unpredictable climatic extremes of prolonged drought and floods. This was well demonstrated by Hacker (1984) in a study of major mid-storey shrubs in a grazed mulga shrubland in the Leonora area of the southern WA rangelands.

For this reason, the model has not been adopted for practical or routine application in the shrublands of Western Australia and therefore will not be considered in depth any further. For the interested reader, Westoby (1979/80) provides particular examples of vegetation response dynamics which do not fit the Clementsian model. The Westoby model is now considered in more detail.

2.2.3.2 Westoby Pulse-Response Model

The Westoby model (Westoby 1979/80) of arid rangeland vegetation dynamics incorporates four principal elements. They are:

i. Asymmetry of plant competition,
ii. Vegetation - soil linkage,
iii. Grazing impact on plant life-form competitive advantage, and
iv. Climate and weather impact on plant life-histories and growth-forms.

Used in different combinations, the model explains both classical range succession and non-equilibrium vegetation dynamics. In essence, the model recognises that low-frequency or episodic weather events and sequences of events, together with grazing and other perturbations such as fire and storm, are key drivers of vegetation change. Although Westoby (1979/80) did not give his model a specific name, it has been referred to as a pulse-response ecological model; it shall be referred to here as the Westoby Pulse-Response model. The four elements of the model are briefly explained below.

i. Asymmetry of plant competition

This element pertains to the outcome of interspecific competition and is fundamentally related to the availability of light to individual plants. In most competitive situations, an adult plant, irrespective of species, life-history or growth-form, will outcompete seedlings. Using the examples given by Westoby (1979/80), perennial grasses can outcompete shrub seedlings but are defeated by adult shrubs. Likewise, annual grasses can outcompete perennial grasses and shrub seedlings but are defeated by adult shrubs or even by tillers of established perennial grasses.

This aspect, a form of positive frequency-dependence in vegetation dynamics, is further explored in Chapter 4 in the development of an indicator of plant assemblage viability as part of an overall measure of range condition or health.

ii. *Vegetation-soil linkage*

This model element recognises the dynamic relationship between plants and soil. Plants affect soil properties and soils affect plant growth (Westoby 1979/80) but the relationship is not simple and direct due to the presence of lag, anisotropy and variable weather sequences. Westoby (1979/80) describes several examples of this relationship, one of which concerns arid shrublands on poor soils, a common situation in the shrublands of Western Australia. Here, a marked reduction of shrub density due to overgrazing could lead to the loss of the thin, relatively nutrient-rich upper soil horizon through accelerated erosion by wind and/or water, leaving a long-lasting, unproductive smooth, indurated 'hardpan' or 'scalded' surface.

The linkage envisaged in this model element is that there is a strong spatial association in the distribution of soil nutrients and plants, the "survive by mutual support" - idea (Westoby 1979/80 p.173). It is interesting to note that this relationship has been firmly established by more recent work and developed into a field technique for assessing landscape functionality and soil surface condition (Tongway & Hindley 2004). As with the previous model element, this aspect is further explored below in the discussion of the Trigger-Transfer-Reserve-Pulse model of Ludwig *et al.* (1997) and in Chapter 4 as part of an overall measure of range condition or health.

iii. *Impact of grazing on plant life-forms*

The third element in the model concerns how grazing pressure is manifest amongst different plant species. Westoby (1979/80) discerns two ecological situations: (1) where biomass production is large and a high proportion is regularly removed by grazing or fire, and (2) where biomass production is much less and only a small proportion is removed by grazing and rarely by fire.

Situation (1) is applicable in many grasslands and savanna-grasslands where there is little opportunity for species to escape herbivory, fitting the Clementsian range succession model well. This situation is not applicable to the shrublands of Western Australia and is not considered further.

In contrast, ecological situation (2) is applicable. In the arid shrublands of Western Australia, the vegetation is open enough for selective herbivory to operate, thereby disadvantaging the preferred, more palatable plant species. Using Australian pastoral terminology, borrowed from American range ecologists, these favoured plants are termed ‘decreasers’ because under set stocking, their abundance usually decreases, in contrast to ‘increasers’ which because they are usually avoided by herbivores, generally increase in abundance over time and are potential weeds. Species that are neither highly preferred nor avoided are termed ‘intermediates’.

As with the previous model element, this driver of vegetation dynamics is further explored in Chapter 4 as part of an overall measure of range condition or health.

Westoby (1979/80) offers a number of factors related to plant species life-history or growth-form which are involved in selective herbivory; the factors are listed below in no particular order of importance:

a. Grazers prefer plants which maximise single-bite forage capture.

b. Grazers select against individual plants with a high proportion of dead, twiggy or woody material.
c. Previously browsed individuals are preferred.
d. Plants with foliage above herbivore browse reach (approximately 1.5 m for sheep) are protected; the population response to grazing pressure is therefore dependent on herbivore preference for the juvenile plants.
e. Set stocking disfavours perennial plants for two reasons; first, biomass productivity varies with season whilst forage demand changes little; and, second, unlike ephemerals, perennials continue to photosynthesise long into drought and hence continue to provide consumptive value to herbivores but are themselves, unable to continue their reproductive cycle until soil moisture conditions improve. Although not explicitly stated by Westoby (1979/80), it is likely that failure to take into account these basic aspects of perennial shrubland plant dynamics is the fundamental cause of overgrazing and environmental degradation.
f. Plants vary in consumptive value to herbivores through a complex combination of factors such as nutritional content, phenological status, digestibility and defences against herbivory (physical, chemical or symbiotic); taken together, these factors constitute the concept of plant palatability to herbivores within the broader context of herbivore grazing selectivity and utilisation (Vallentine 1990; Vesk & Westoby 2001; Russell & Fletcher 2003).

iv. *Impact of climate and weather on growth forms*

The fourth element of the Westoby model pertains to the prediction of plant population responses and vegetation assemblages in relation to rainfall sequences, based on plant growth-forms and life-histories. Rainfall sequences are considered at the seasonal and climatic scales of influence.

The core theme or message is that "growing conditions for plants in arid areas cannot be characterised by an average degree of dryness, even with a measure of variation attached. Rather, there occur sequences of excellent growing conditions, difficult but usable conditions and drought. Different life-histories and growth-forms use these sequences in different ways" (Westoby 1979/80, p.177). Westoby identified three main types of soil moisture conditions, termed 'types of time', and characterised for each, the growth rate response for different growth-forms. For any plant to survive, it must maintain hydrated xylem to each meristem. Each growth-form represents a different survival strategy, utilising fundamental plant processes such as maintaining hydrated tissue, deployment of new photosynthetic tissue, conversion of photosynthate to seed and the development of particular root systems at different times. The key point for plant life-forms is that none know the time of onset, duration and severity of drought ('type III time'). Relative survival advantages change as drought progresses or, simply, with drought duration. Evergreen perennials with xerophyllic leaves have the best chance of surviving long droughts but have reduced reproductive advantage compared to stem-succulents and late-shedding, xerophyllic-leaved perennials in shorter duration droughts. When no drought occurs, ephemerals have clear reproductive advantage over perennial life-forms.

A further aspect considered by Westoby (1979/80) in this model element is the phenomenon of different life-forms occupying the same soil volume. It is simply explained by (1) the different use of types of time by the different life-forms, and (2) by competition between comparable life-forms. In this way, Westoby argues, frequency-dependent competition drives "stable co-existence to arise between two or more plant growth-forms or life-history strategies" (Westoby 1979/80, p.181).

In conclusion, Westoby (1979/80) makes two important points. First, since vegetation dynamics in rainfall-limited arid shrublands are driven more often by response to episodic events (big rains, long drought); rather than average conditions, an equilibrium model of range management such as Clementsian range succession is inappropriate. Second, to allow the re-establishment of cohorts of desirable perennial shrubs, paddocks should be temporarily destocked to allow recruitment following germination events in order to provide a sustainable forage resource.

2.2.3.3 Stafford Smith and Morton Model

In the arid landscape ecological model developed by Stafford Smith & Morton (1990), the indirect gradient variables (terminology of Austin 2002) of geology (substrate), topography (position and slope) and the resource gradients of nutrients (soil fertility) and water (rainfall variability) are the primary drivers of the diversity, distribution and persistence of plants and animals. In particular, it is the combination of infrequent, exceptionally large rainfall events, the very flat landscape and generally highly weathered, nutrient-poor regolith that have fundamental and widespread effects on the distribution of plants and on the distribution and abundance of higher trophic level consumers.

The Stafford Smith and Morton model is now considered in more detail. The model consists of a broad-scale, descriptive, proposition-based framework containing key elements of ecosystem function in arid Australia. In terms of the Austin (2002) three-component model structure referred to earlier, this is the ‘ecological model’ component, required for effective examination of functional relationships between species and environment. The framework reflects fundamental ecological relationships between four principal components in the arid landscape, in particular, the infertile soils, the highly variable and highly unpredictable climatic events of long dry periods and flooding rains ('big rains'), the array of life-history strategies and the domination of vegetation assemblages by long-lived perennial plants.

The relationships are described in terms of 15 propositions, grouped into three general areas – the physical environment (three propositions), consequences for adult plants (five propositions) and consequences for faunal consumers (seven propositions). These are outlined below in Table 2.1 as a useful summary of the descriptive model.

Table 2.1 Stafford Smith and Morton ecological model – summary of propositions (from Stafford Smith & Morton (1990 p.259)

PHYSICAL ENVIRONMENT

1. Rainfall temporal and spatial unpredictability.
2. Big rains structure the physical and biotic environment.
3. Ancient, infertile landscape.

PLANT STRUCTURE and FUNCTION

4. Highly patterned plant production.
5. Soil moisture and diverse plant life histories.
6. Soil fertility controls plant digestibility.
7. Plentiful carbohydrate.
8. The importance of fire

FAUNAL ASSEMBLAGES

9. Food availability (rather than water) governs animal life.
10. Herbivore abundance is constrained by plant productivity.
11. Soil infertility favours termites.
12. Continuous production supports persistent consumers.
13. Ant and termite colony food storage strategy buffers plant productivity pulses.
14. Patterns of higher-order consumers.
15. Consumer stability is higher than expected.

Stafford Smith & Morton (1990), in their concluding discussion, emphasise the need for ecologists to consider the profoundly important effects of spatial heterogeneity in Australian arid zones, in particular, the high degree of spatial variability of plant biomass productivity and its implication on the distribution pattern of higher-order consumers.

A comprehensive examination of the Stafford Smith and Morton model by Southgate, Allan & Ostendorf (2006), using the Tanami Desert as a test landscape, found that the model is not yet adequate for predicting change or responses such as species distribution to environmental drivers. Anthropogenically induced changes were not specifically considered in this test. Whilst agreeing on the importance of rainfall spatial and temporal variability, Southgate, Allan & Ostendorf (2006) concluded that the lack of incorporation of the direct gradients of atmospheric heat (temperature) and humidity (rainfall) may be the greatest limitation in applying the model in a variety of arid regions of Australia. For example, in the Tanami, strongly associated with these climatic gradients are pronounced vegetation cover, structure and composition changes from low woodland assemblages in the north (higher temperature and humidity) to sparse shrublands in the south. A similar pattern has been found in the Great Sandy Desert, Western Australia by Cols and Whitaker (2001, cited by Southgate, Allan & Ostendorf 2006).

Finally, Austin (2002) observes that ecological models based on direct gradients and resource gradients are generally less robust and less applicable across a wide range of geographic regions.

2.2.3.4 Trigger-Transfer-Reserve-Pulse Framework

The following description of the Trigger-Transfer-Reserve-Pulse (TTRP) conceptual model of arid land functional relationships and processes is based on the work of CSIRO researchers John Ludwig, David Tongway, Ken Hodgkinson, David

Freudenberger, Jim Noble, Graham Griffin, Neil MacLeod, Joel Brown and others. Their work was published in a landmark book entitled “Landscape Ecology – Function and Management” in 1997 (Ludwig *et al.* 1997). Their approach is called landscape function analysis as it links landscape patterns to ecological function.

Soil and vegetation patterns in arid lands have long been recognised but the key insight provided by the CSIRO work was the elucidation of the extent and importance of vegetation patches, at multiple spatial scales, in landscape ecological processes and functions. The interaction of vegetation patches and inter-patches determines how scarce but vital resources for plant growth, water and nutrients, are retained within ecosystems.

The TTRP framework is shown in Figure 2.1. It has four main process components – trigger, transfer, reserve and pulse: - each is described in turn below.

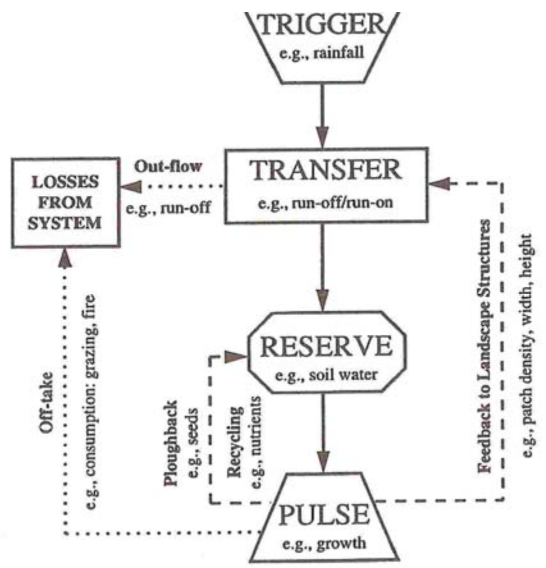


Figure 2.1 The Trigger-Transfer-Reserve-Pulse conceptual model of landscape function for arid and semi-arid environments (from Ludwig *et al.* 1997, p.4).

Rainfall is the trigger to which ecosystems respond. Although moderated or regulated by the status of key nutrients and other factors (e.g. ambient temperature), rainfall initiates or accelerates a number of biogeochemical processes between soil and plants, resulting in biomass productivity pulses. Rainfall events are, however, highly variable in space, time, intensity and amount – a characteristic of most arid and semi-arid environments, hence the label or descriptor 'water-controlled' or 'water-limited' given to these environments.

Wind and water are agents of re-distribution of materials across the landscape. Downslope transfer processes involving water such as run-off, run-on, run-through, are important considerations. For most arid rangeland environments, the key to understanding degradation is to understand the erosional-depositional behaviour of water in the various parts of the landscape or catchment. However, in some environments such as arheic areas, for example, most sand and karst plains, wind may be the dominant agent.

Places where materials are deposited are called reserves. They are relatively resource-rich zones or patches of accumulation of water (infiltration) and nutrients (in the form of solutes, organic litter and mineral or rock fragments). These sinks or traps are aptly called 'fertile islands' and occur in different shapes and sizes, and generally form, in plan view, patch-mosaics or distinct patterns such as groves in the case of mulga *(Acacia aneura).* The patterns are observable at a range of spatial scales, generally referred to as landscape patchiness.

Landscape degradation is a reduction in the efficiency of resource capture, arising from the physical breakdown and dispersal of the patches or 'islands of fertility'.

The response to rainfall is called a pulse. In arid and semi-arid landscapes, the size of the growth response is determined by both the bio-availability of resources in the reserve and the size of the rainfall trigger. Thresholds are involved; reserve-held resources need to be above critical levels before rainfall is able to trigger a pulse and, similarly, rainfall amount needs to be large enough. In other words, falls below the threshold amount will not trigger a growth response in quiescent plants, particularly during periods of high evaporation.

The trigger-transfer-reserve-pulse sequence of processes also includes feedback loops. Ludwig *et al.* (1997) distinguish between the feedback of growth pulses (seeds and organic litter) in replenishing the resource reserve (termed 'ploughback'), and the feedback involved in building or expanding patches (termed 'feedback'). Ploughback recycles organic carbon and nutrients into the soil stores through processes of plant litter breakdown and decomposition facilitated by invertebrates and micro-organisms.

Feedback enhances the ability of patches to capture resources. This is done by the recruitment of new plants which increases both the density of plants and the size or extent of the patch. Both feedback processes enable the patch to intercept more water and its load in subsequent rainfall events. This is an important characteristic of properly functioning landscapes and relates directly to one of the attributes, perennial plant density, used in an index of ecological integrity discussed in Chapter 4. Perennial plants exert a strong influence on the transfer and capture of scarce resources.

The last aspect of the conceptual process framework concerns the loss of resources from the ecosystem. Losses occur through outflows and offtakes. Outflows eventuate when surface water flow exceeds the aggregate absorptive capacity of the patches. This may happen even with properly functioning systems when very large rainfall events occur. In the case of poorly functioning or dysfunctional systems, loss occurs with much smaller rainfall events – the 'tiled-roof syndrome' of Hugh Pringle (*pers. comm.* 2005). In these excessively 'leaky' systems, surface water flows are rapidly entrained in gullies, creeks and rivers, carrying essential resources out of the system.

Whilst there are very important processes associated with degradation such as the homogenisation of vegetation, woody shrub invasion, general landscape desiccation through canalisation, reduced water residence time and edaphic drying, these aspects are not specifically dealt with by the TTRP model. The interested reader is referred to excellent descriptions of these processes by Ken Tinley and Hugh Pringle (Tinley 1982; Tinley 1991; Pringle & Tinley 2003; Pringle, Watson & Tinley 2006).

Offtake is simply the loss of nutrients from the system by the physical removal of herbivorous consumers such as livestock.

2.3 Southern Rangelands – Regional Overview of Climate, Geological Setting, Catchment Hydrogeology and Geomorphology

2.3.1 Climate

The southern rangelands extend over about 10 degrees of latitude and 15 degrees of longitude, encompassing a wide range of arid and semi-arid climatic zones. The zonation arises from the interaction of several large-scale rainfall generating processes, seasonal air pressure patterns and geographic patterns of temperature and evaporation.

Annual rainfall ranges from about 350mm to less than 200mm, decreasing from the maritime-influenced coastal regions towards the arid continental interior. However, the pattern of annual evaporation, which everywhere exceeds rainfall, increases from the coast to the interior, leading to a marked annual rainfall deficit (evaporation minus rainfall) ranging from approximately 2,400mm in the coastal zones to more than 3,500mm in the interior. This of course, is an important driver of vegetation-soil water balance relations.

There is also a distinct seasonal rainfall pattern, shown in Figure 2.2. In the northern parts of the southern rangelands, total annual rainfall is dominated by rainfall received during the summer months (November to March) under the influence of tropical rain-bearing monsoon, cyclonic and northwest cloud bands. Winter rainfall (May to September) gradually becomes more dominant in the southern parts of the rangelands due to the influence of rain-bearing 'cold fronts' associated with low pressure systems generated in the southern Indian and Southern Oceans, although for the Nullarbor no distinct seasonal pattern is evident. The resultant pattern of bioclimes is shown in Figure 2.3. Where winter rainfall dominates, the climate is classified as dry Mediterranean-type.

The patterns described above, which are based on long-term or historical data, tell only part of the climate story. The southern rangelands, indeed most of non-tropical Australia, is characterised by highly variable rainfall. Figure 2.4 shows the pattern of variability for Western Australia. There is a very distinct trend of increasing variability southwards from the northern tropical parts and northwards from the southwestern corner of the state, towards the interior. The moderate to extreme variability zones fall in the climatic transition between the northern summer-dominated and southern winter-dominated rainfall patterns. In practical terms, this means that rainfall for most of the southern rangelands is episodic, irregular and unreliable. 'Good seasons' are not typical but long dry seasons are. An appreciation of how long it can be 'between drinks' is gained by an examination of the longest time between rainfall events of different magnitude. Table 2.2 lists this information for several localities in the southern rangelands.

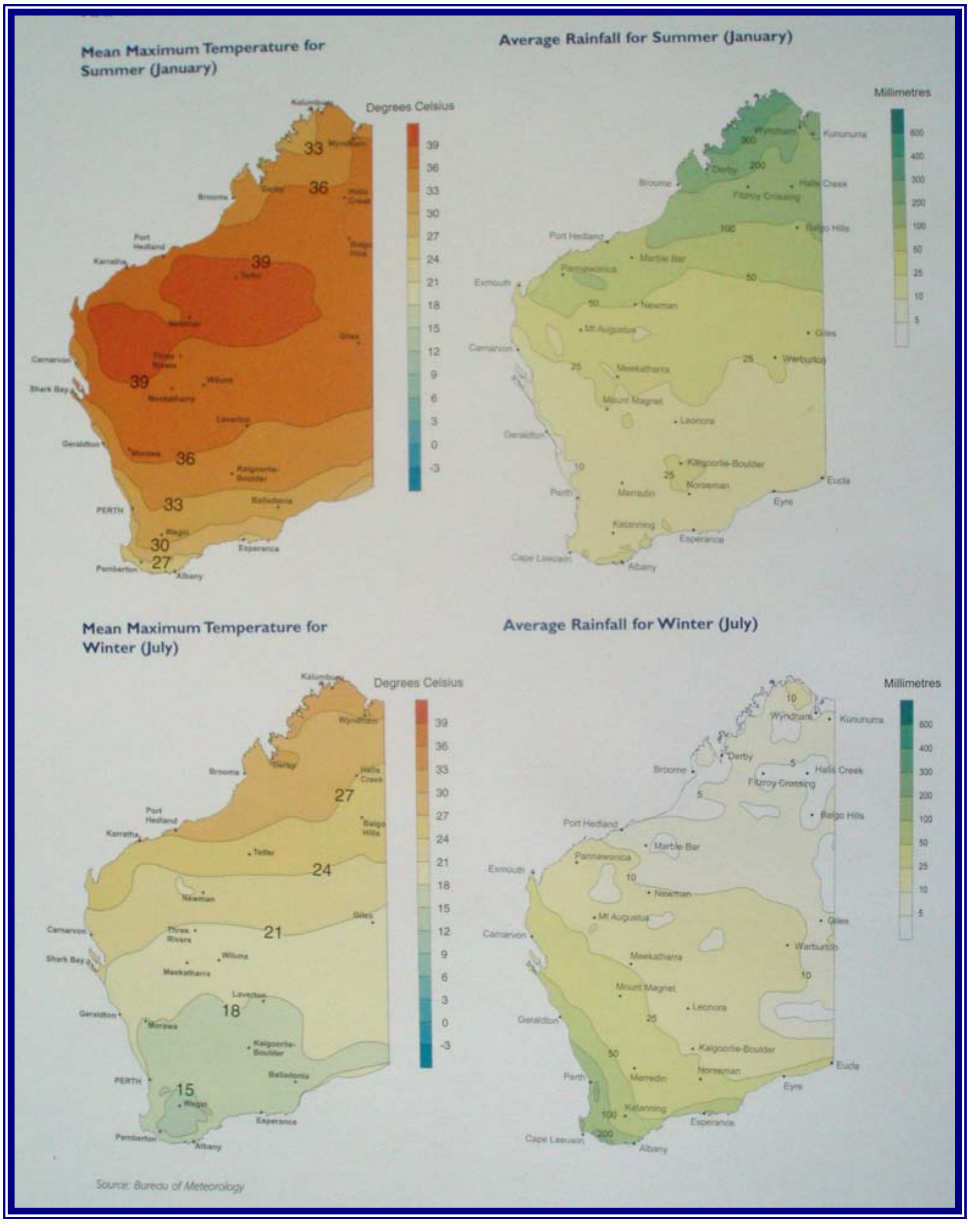


Figure 2.2 Winter and Summer: mean maximum temperature and average rainfall for Western Australia. (from Bureau of Meteorology)

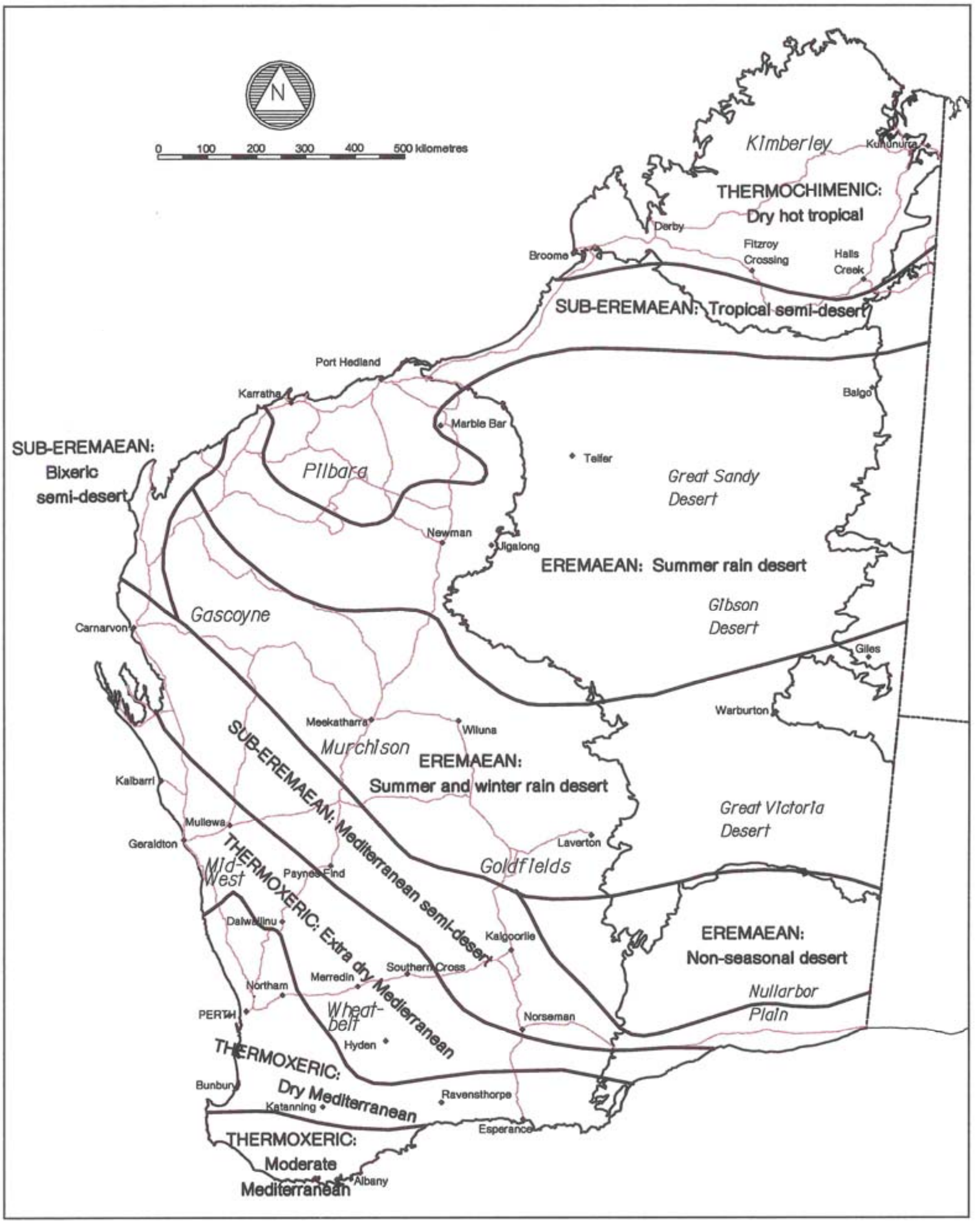


Figure 2.3 Bioclimes of Western Australia; regions, roads and townships also shown.

(source: Beard 1990, reproduced from Tille 2006)

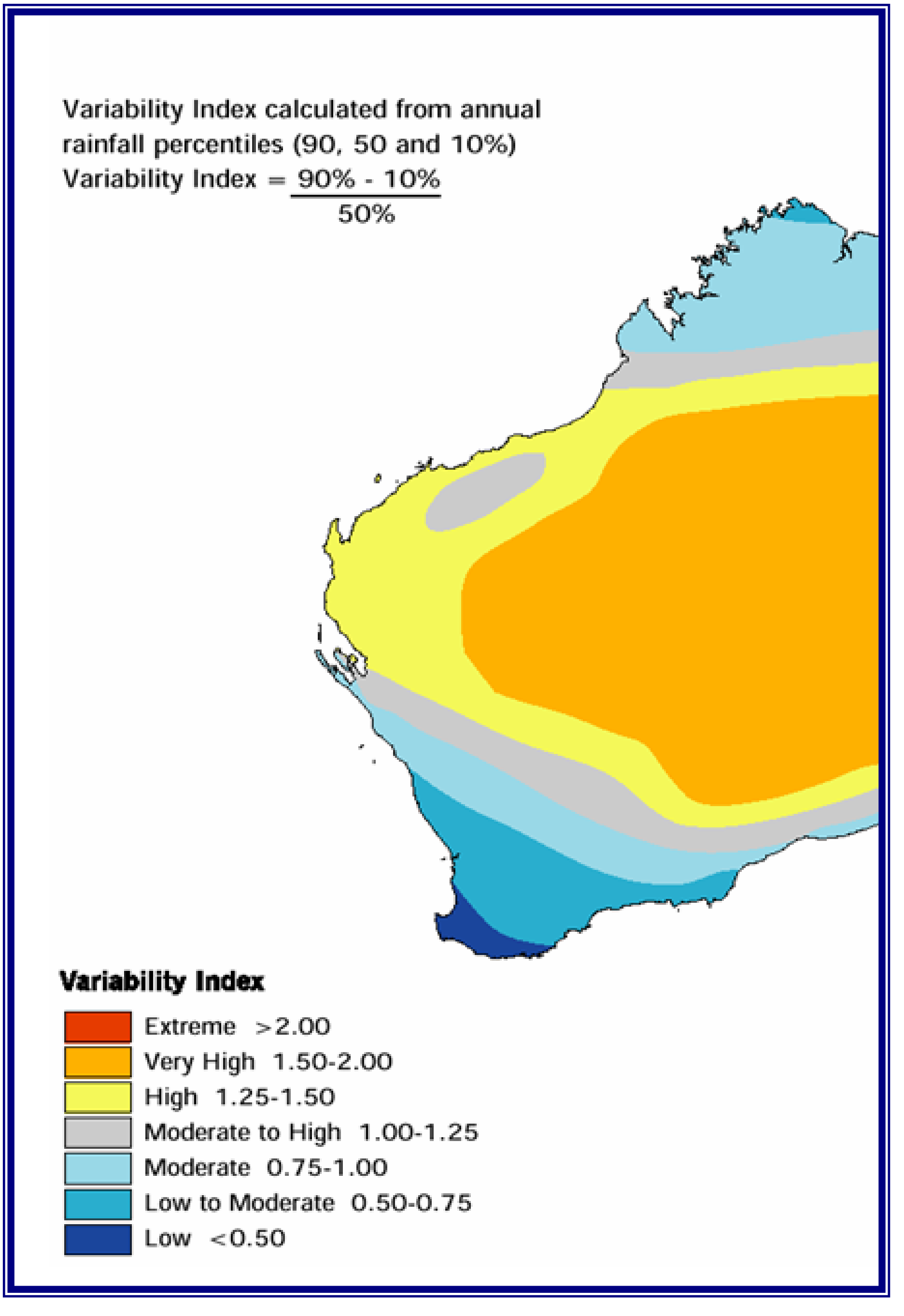
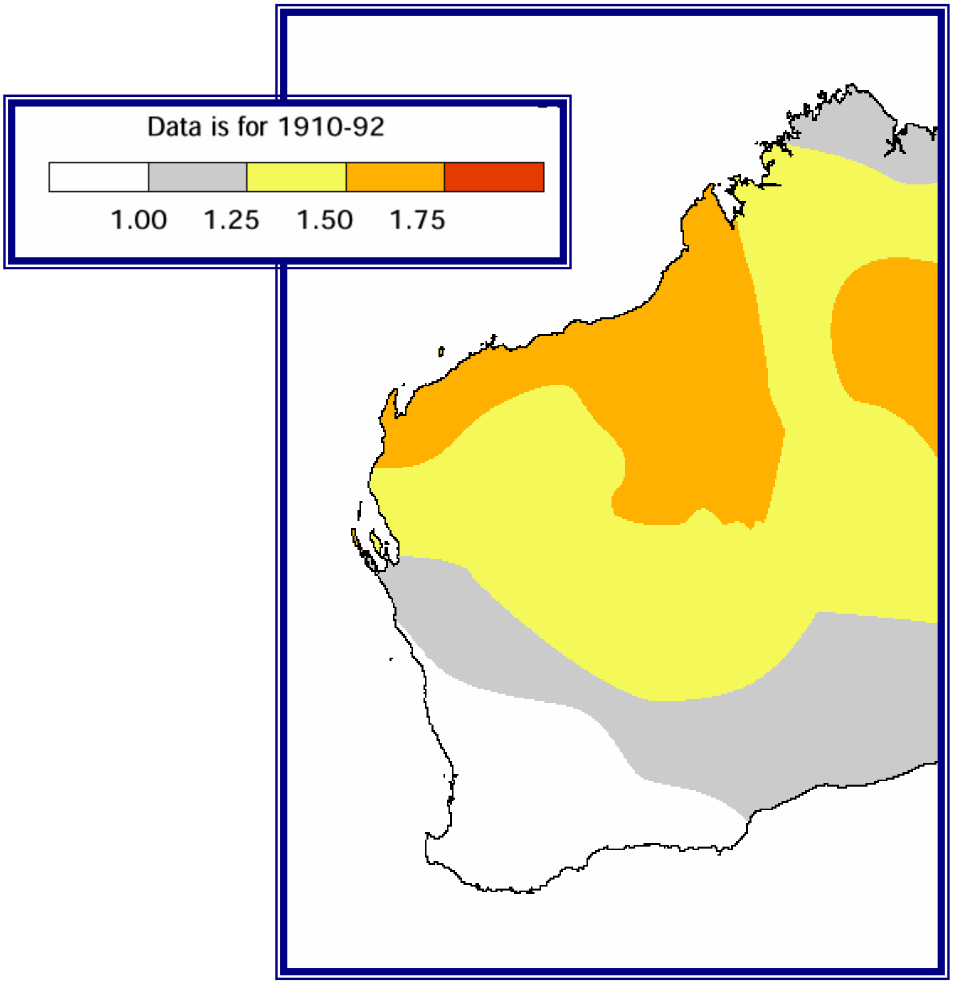


Figure 2.4 Annual rainfall variability for Western Australia. **(from National Climate Centre)**



Explanation:

This map shows the variability of Western Australian rainfall relative to other parts of the World with similar mean annual rainfall.

*White areas indicate where rainfall is **less variable** compared to other global areas with similar mean annual rainfall.*

*Shaded areas indicate where rainfall is **more variable** than expected from the global pattern.*

Figure 2.5 Western Australian rainfall variability relative to global patterns. (Source: National Climate Centre)

Table 2.2 Maximum duration (years) between rainfall events of different magnitude (data from Rainman©).

Locality	***Rainfall Event Magnitude***		
	25mm	**50mm**	**100mm**
Yanrey (Ashburton)	2.6	4.3	9.2
Boolathana (Carnarvon)	2.1	4.0	20.9
Meekatharra (east Murchison)	3.8	6.8	15.8
Bulga Downs (Goldfields)	2.8	6.5	15.1
Rawlinna (Nullarbor)	4.5	7.9	26.1

In relation to other semi-arid and arid regions of the World with similar annual average rainfall, the variability of rainfall in Western Australia (and in most of Australia) is considerably higher (Figure 2.5). Clearly then, the nature of the climate, together with the ancient landscape (described below), interact to limit the availability of surface water over extensive tracts of the rangelands. For this reason, the behaviour of surface water flow across the landscape is critical to its ecological health. However, somewhat surprisingly, this aspect of range ecology and the related characteristic of rainfall variability, are still not widely appreciated or integrated as fundamental drivers in range management grazing strategies and decision making in the southern rangelands.

2.3.2 Regional Geological Setting

The southern rangelands encompass portions of several major geological provinces, each distinguished by particular combinations of rock ages, types and structural or tectonic deformation. Each province influences landscape development in particular ways.

In the following description, the main crystalline basement provinces, including principal orogenic (tectonic collision) zones are outlined first, and then, in approximate younging order, the overlying sedimentary basins. Figure 2.6 illustrates the main tectonic (geological) provinces and units in Western Australia.

Most of the southern rangeland is underlain by the Yilgarn Craton. This very large province forms part of the continental basement of southern Western Australia and is exposed over large areas. The craton is composed of Archean-age (> 2,500Ma) granite and greenstone rocks. The greenstones occur as linear, generally north-northwest to south-southeast trending belts of highly deformed (folded and faulted) rocks into which the granites have later intruded at various times during the Archean. 'Greenstone' is a widely used general term referring to geologically related layered sequences of mafic (mainly dark coloured minerals) and felsic (mainly light coloured minerals) volcanic rocks, banded iron formations, chert and clastic sedimentary rocks such as sandstone, siltstone and shale. The variety of rock types constituting the greenstones engenders a greater variety of topographic expression compared to the more uniform granite country. All of the Archean rocks have been metamorphosed to varying degrees, with the highest grades usually near granite-greenstone contacts. These rocks host substantial gold, nickel and base metal deposits, many of which are mined.

Bounding the Yilgarn Craton to the north is a geologically complex area (Figure 2.6), comprising mainly Proterozoic-age (500 - 2,500Ma) volcanic and sedimentary rocks originally deposited in a series of contiguous basins (Collier, Yerrida, Earaheedy and Officer Basins). The older basins were later deformed as part of the Capricorn Orogen and others as part of the Paterson Orogen. The undeformed basins (mainly the Officer Basin) belong to a much larger entity known as the Centralian Superbasin, although the superbasin is only exposed in the northwestern and far eastern parts of the southern rangelands. The complexity of this area is a result of tectonic collision between the Yilgarn and Pilbara Cratons. A portion of the

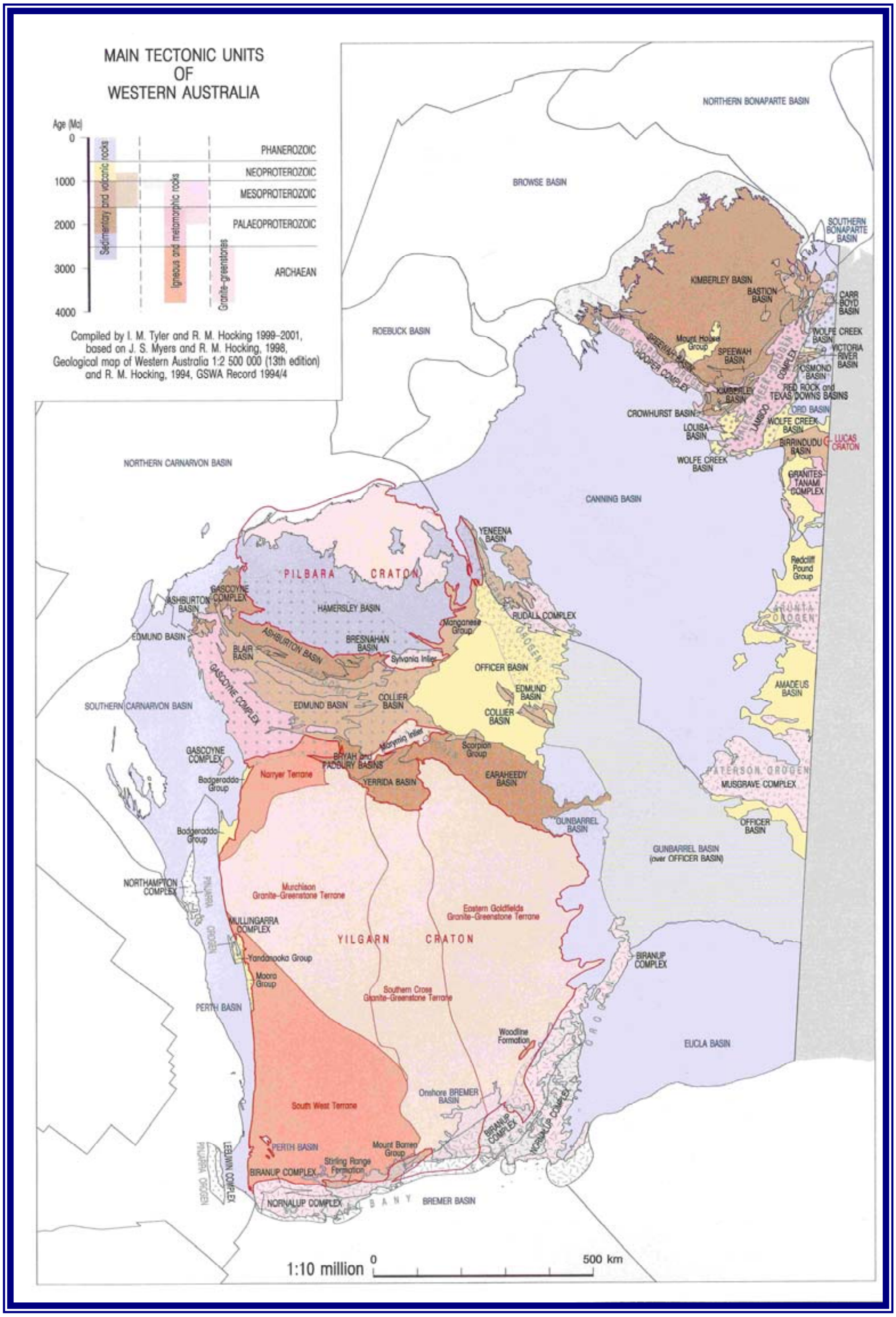


Figure 2.6 Tectonic (geological) provinces of Western Australia. **(from GSWA 2003 Atlas of Mineral Deposits and Petroleum Fields)**

Paterson Orogen (Musgrave Complex) is also exposed in the far eastern parts of the arid interior.

The Pilbara Craton comprises two major geological entities – an older Archaean granite-greenstone basement terrane formed between 3,600Ma and 2,800Ma, and a younger sequence of Archaean-Proterozoic volcanic and sedimentary rocks known as the Mount Bruce Supergroup. This layered sequence, which includes extensive iron-rich formations, occupies the Hamersley Basin and was deposited between 2,700Ma and 2,400Ma. In the northern and eastern parts of the craton, the granite-greenstone terrane is exposed at the surface but to the south; it is unconformably overlain by the Hamersley Basin.

A second major Proterozoic tectonic collision zone underlays the southern rangeland. Known as the Albany-Fraser Orogen (Figure 2.6), it bounds the southeastern margin of the Yilgarn Craton and consists of granite, gneiss and, mafic and ultramafic igneous rocks. Fraser Range is a conspicuous landscape feature of this geological province.

Overlying the older crystalline basement and orogenic zones are a number of much younger sedimentary basins. Situated along the western margin of the Yilgarn Craton and occupying all of the western coastal parts of the southern rangelands is the Southern Carnarvon Basin. This large sedimentary basin, which shares much of its geological history with two other basins, the Northern Carnarvon Basin to the north and the initially contiguous Perth Basin to the south, contains a thick sequence of marine and lesser terrestrial sedimentary rocks ranging in age from Silurian at the base, up through Devonian, Early Carboniferous and Upper Carboniferous - Permian sequences. In parts, a veneer of Cretaceous - Cainozoic sequences are preserved at the top of the sequence. The basin extends approximately 650km from the Murchison River area north to the Cape Range area where it becomes the Northern Carnarvon Basin. Basin width is approximately 500km, with the western margin occurring about 200km offshore and the eastern margin on-lapping or in fault contact with crystalline basement rocks of the Yilgarn Craton onshore. The geological evolution of the Southern Carnarvon Basin is integrally tied to the break-up of Pangaean and Gondwanan super continents, with the west Australian continental margin shaped by a protracted sequence of major tectonic rift events.

Lastly, occupying the eastern-most parts of the southern rangelands is a series of large undeformed Phanerozoic-age (< 500Ma) sedimentary basins (Figure 2.6) overlying parts of the previously mentioned Archaean and Proterozoic provinces and zones. The main basins are the Canning (to the north of the southern rangelands), Gunbarrel (central parts) and the Eucla (in the south). Most contain thick sequences of marine and continental clastic sedimentary rocks such as sandstone, siltstone, shale and limestone. The Eucla Basin, located in the southeast of the rangelands, is the youngest of the basins and is largely filled with marine limestones. These rocks, because of their high carbonate content, have created extensive alkaline soils, which in turn, have constituted an effective edaphic barrier to genetic exchange between the south western and south eastern parts of the continent, and have thus contributed to the rich plant endemism characteristic of southern Western Australia.

2.3.3 Palaeoclimate and Regional Physiographic Setting

The contemporary pattern of landforms and associated regolith in the southern rangelands is simply a 'snapshot' in geological time of continuous landscape change. In summary, the pattern reflects the latest major phase of geomorphic and climatic processes, specifically the last Cretaceous continental separation (from Antarctica) and gentle regional uplift during the Late Miocene- Early Pliocene (about 10 million years ago) within a stable continental tectonic framework. Some additional information regarding climatic and geomorphic events leading to the current situation are provided.

For most of the last 250 million years (since the end of the Permian Period), much of Australia, including the present-day arid zones, had a humid to subhumid climate, with sufficient rainfall to support extensive woodlands including, at times, rainforest. Rainfall in the Eocene Epoch (55 - 34 Ma), before onset of the prolonged general drying phase (which has continued to the present), was able to maintain a number of major rivers, some of which flowed westward to the Indian Ocean and others southward to the proto-Great Australian Bight. By Late Miocene times (~ 12 Ma), the developing aridity had substantially reduced river discharges, and by earliest Pliocene times (~ 5 Ma) gypsum had begun accumulating in discontinuous saltlakes, now the conspicuous vestiges of the earlier great rivers (Thomas 1989; Young & Young 2001).

During the last 40 million years, since Australia separated from Antarctica and began its northward drift, the geological history of Western Australia is characterised by the lack of mountain building and volcanic events. Whilst there has been broad flexing of the continental interior causing changed drainage patterns, uplift along the coastal margins causing drainage reversals, capture and rejuvenation, and marine regression and transgression in response to global-scale geological and climatically induced sea-level changes, the overall prolonged geological stability has allowed extensive erosion, landscape stripping and deep weathering to occur (Allen 1997). This has created the extensive flat but diverse landscape so characteristic of much of the southern rangelands. This flat landscape is known as the Great Australian Peneplain or Western Plateau (Jennings & Mabbutt 1986). The major physiographic divisions are shown in Figure 2.7.

Although the process continues, much of the denudation of the Western Plateau occurred during wet phases in the Jurassic and Cretaceous Periods and the

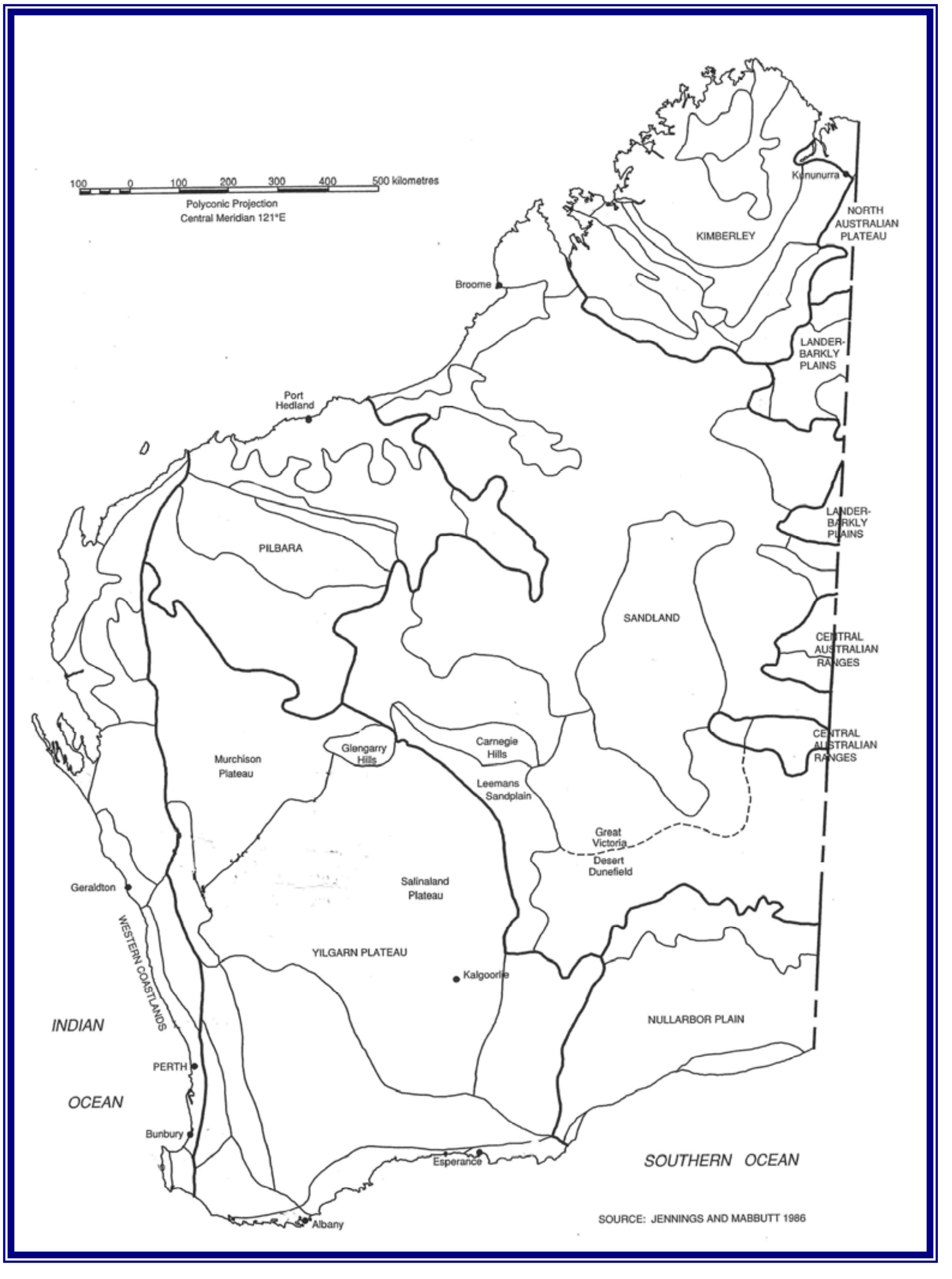


Figure 2.7 Physiographic provinces and regions of Western Australia (from Jennings and Mabbutt 1986).

Paleocene to Oligocene Epochs, prior to onset of the prolonged drying phase in the Miocene Epoch. It has been estimated that the Yilgarn Craton land surface has been lowered by 350 to 400 metres, at erosion rates between 5 and 2m/Ma (Young & Young 2001). The resulting soils are extensive, diverse in character, old and frequently indurated, and include acid, highly leached kaolinised soils, neutral to alkaline soils of high base (calcium, magnesium, iron) status and extensive duricrusts (silcretes, calcretes, ferricretes), frequently overlain by extensive siliceous aeolian sands of the sandplains and dune fields (McKenzie *et al.* 2004). The present-day sandplains and dunefields, many of which formed as long ago as 125,000 years, had their most intense development during the last major arid period and associated low sea levels (Last Glacial Maximum) from about 28,000 to 10,000 years ago (Young & Young 2001).

The southern rangelands include four major physiographic provinces (Jennings & Mabbutt 1986) namely, the Desert Sandland, Salt Lake or Salinaland, Nullarbor Plain and Pilbara (Figure 2.7). The Desert Sandland Province extends northeast from Kalgoorlie. It consists of extensive undulating sand and gravel plains, dune fields, low granite or sandstone ranges and breakaways (erosional escarpments) and strings of shallow salt lakes. The salt lakes are part of a system of palaeodrainages that drain either northwards into the Disappointment and Percival Palaeorivers and ultimately into the Oakover - DeGrey Rivers flowing to the Indian Ocean, or southeast to the margin of the Nullarbor Plain. These drainages flow only after heavy rains.

The Salt Lake Province, also known as the Salinaland Plateau (Figure 2.7), lies to the west of the Sandland Province and is characterised by a large number of extensive shallow salt lakes or playas. Most are curvilinear in shape, now forming chains of very low gradient depressions in the great peneplain. They originally developed as an active integrated drainage system during wetter periods from the late Cretaceous Period. Subsequently, during the Eocene Epoch following gentle epeirogenic uplift, the region was subject to erosion, drainage aggregation and stagnation (inactivity) due to sediment infill and encroachment by sand plains and dunes during dry periglacial periods. Now, the palaeodrainages are active only after rare heavy rainfall. A regional drainage divide splits this province. Drainages in the western portion are exorheic, eventually linking up with permanent or semi-permanent rivers discharging at various points along the coast into the Indian Ocean. The drainages in the eastern portion, however, are endorheic, eventually discharging, albeit rarely, into the Eucla Basin on the western and northern margins of the Nullarbor Plain. Figure 2.8 shows the pattern of palaeodrainages. There are four large, broad and sub-parallel systems extending from a regional catchment divide to the west and draining to the southeast; in order from north to south, they are the Carey, Raeside, Yindarlgooda and Lefroy Palaeorivers, and two draining to the north, the Throssell and Baker Palaeorivers. Between the salt lakes, the landscape consists of undulating sandplains and minor dune fields, granite hills and rises, greenstone hills and rugged banded-iron formation strike ridges, duricrust (lateritic) breakaways, alluvial plains and calcrete flats.

The Nullarbor Province (Figure 2.7) occurs in the southeast part of the southern rangelands. It consists of a vast, very flat limestone plateau known as the Bunda Plateau and to the south, a narrow plain known as the Roe Plains, marginal to the western part of the Great Australian Bight. Extensive coastal dunes occur on the Roe Plains. The coastal margin includes two very substantial unbroken lengths of sheer vertical cliff, the Baxter (60 to 90m high) and Bunda Cliffs (40 to 75m high). The boundary between the Bunda Plateau and Roe Plains is the wave-cut scarp (eroded sea cliffs) of Hampton Range or Tableland, and includes its western extension, the Wylie Scarp separating the narrow Israelite Plains from the main plateau (Mitchell, McCarthy & Hacker 1988).

The Nullarbor is reputedly the World's largest arid zone karst region. The limestone rocks are generally highly cavernous and permeable, allowing episodic discharge

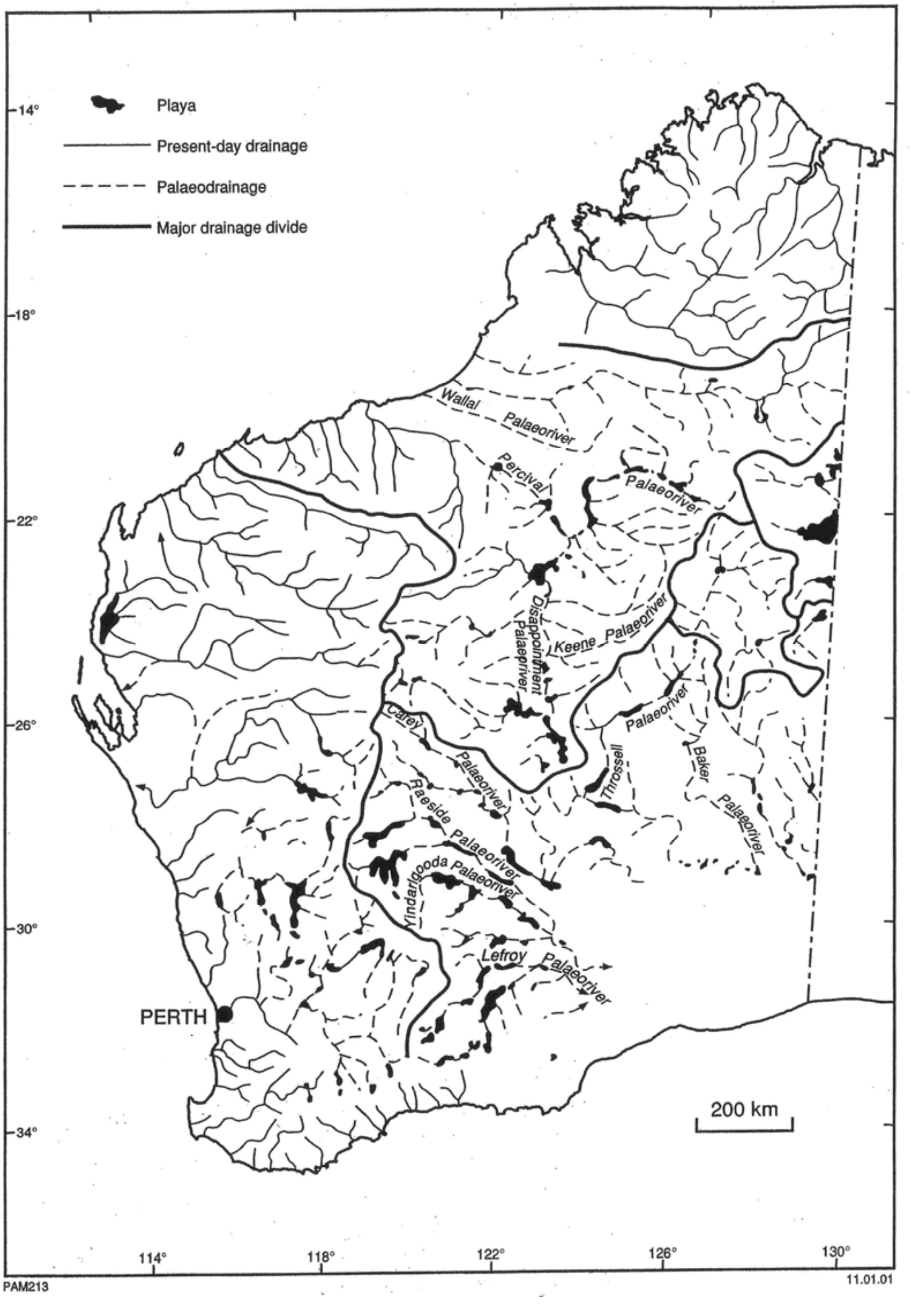


Figure 2.8 Drainage system and regional drainage divides in Western Australia. **(from Allen 1997)**

from the palaeodrainages and rainfall to rapidly infiltrate. Residual clay and kankar (concretionary calcium carbonate) form broad flat plains, and, diffuse drainage tracts with claypans and dongas between low limestone rises occur in parts. There are no major coordinated surface drainages.

The northern part of the southern rangelands extends into the Pilbara Physiographic Province. Geomorphically, the province consists of four distinct regions, comprising coastal flats to the west, alluvial plains and valley floors (notably the Fortescue Plains along the middle and upper reaches of the Fortescue River), strike ridges and low hills to the north, and an extensive dissected plateau to the south through which the Fortescue River has cut. The plateau is a partly eroded Cainozoic peneplain known as the Hamersley Surface. The rivers and creeks only flow after heavy rains, but there are numerous springs and permanent waterholes in this very scenic region. Grasslands occupy most of the province with small areas of shrubland dispersed throughout.

2.3.4 Hydrogeological Aspects

The availability of water is essential for life and historically, has strongly influenced the movement of people, the location of trade routes and settlements. Today, it also underpins the development and utilisation of natural resources, including mining and pastoral activities. The following description provides an overview of the occurrence of groundwater resources in the southern rangelands from a geological perspective. More detailed information, including additional maps and diagrams, are contained in Allen (1997) and Johnson, Commander & O'Boy (1999).

Throughout the rangelands, the availability of water for domestic consumption, stock use and mining purposes has been a major issue. For example, following the discovery of gold in 1892 (Coolgardie) and 1893 (Kalgoorlie) in the region now known as the Goldfields, the scarcity of potable water, which had caused numerous deaths by thirst and from outbreaks of hygiene-related diseases amongst the thousands of gold-rush prospectors, was substantially alleviated in 1903 by completion of the Mundaring (Perth Hills) to Kalgoorlie water pipeline. Major expansion of the gold and base metal industry in the Goldfields from the late 1960s has been largely facilitated by the availability of saline and hypersaline groundwater. The pastoral industry throughout the region also relies on numerous bores and wells, utilising mainly shallow unconfined groundwater sources of water suitable for stock, mainly sheep. There are also numerous towns and communities wholly or partly reliant on potable groundwater supplies.

The amount of groundwater available in a particular area depends on the water yield characteristics of the regolith or underlying rocks. Zones that yield useful amounts of water are termed aquifers. In the southern rangelands, three types of aquifer occur:

- Surficial aquifers consisting of alluvial (including palaeodrainage deposits), eluvial, duricrust, aeolian and lacustrine sand and gravel deposits, overlying either sedimentary or igneous/metamorphic rocks.
- Sedimentary aquifers consisting of lithified sedimentary deposits such as sandstone, conglomerate and limestone, occurring in sedimentary basins.
- Fractured rock aquifers consisting of igneous or metamorphic rock and large quartz veins that have been fractured well enough to store water, and the weathered zone overlying fresh rock.

The location of the three types of aquifer relate very closely to the geology shown in Figure 2.6.

Aquifers are usefully further categorised as either unconfined or confined; the distinction having a strong bearing on pumping behaviour and management of the environment. Qualitative differences between unconfined and confined aquifers are tabulated by Allen (1997 p.19).

The amount of recharge to an aquifer depends on the type of aquifer, topography, vegetation cover, and the amount and intensity of rainfall. For most of the southern rangelands, recharge is mainly from intense episodic rainstorms and cyclonic rain depressions, in contrast to the highly seasonal recharge in the northern and far southwestern parts of the state. Groundwater moves under the influence of gravity from recharge (intake) zones to discharge, laterally and vertically through fractured rocks, the weathering profile, permeable sedimentary rocks and surficial deposits. The overall groundwater movement is laterally from the drainage divides towards the drainages. In the Salinaland and Desert Sandland Divisions, water table formlines and groundwater isohalines indicate that the highest water tables and lowest-salinity water occur along the divides between the palaeodrainages, implying that most recharge occurs on the crests and flanks of these divides in areas of exposed fractured rock and quartz veins, and on sandplains and high-level laterite flats (Pringle, Van Vreeswyk & Gilligan 1994). In terms of groundwater quality, there is a very consistent salinity pattern changing from low in the vicinity of drainage divides to high salinity near salt lakes. This catchment-scale pattern is part of a much broader, regional pattern of groundwater chemistry across the Yilgarn Craton. In the southern parts, groundwater is highly saline and acid, progressively becoming neutral and much fresher to the north.

The largest supplies of potable to low salinity water are obtained from faults, shears, large quartz veins and pegmatites cutting granite, and from along granite - greenstone contacts (Pringle, Van Vreeswyk & Gilligan 1994). Water from greenstones tends to be more saline than water from granites in similar locations, and palaeodrainages produce the highest salinity water. Potable water sources in the western Eucla Basin have yet to be comprehensively investigated.

3 Overview of the Western Australian Rangeland Monitoring System

Chapter 3: Overview of the Western Australian Rangeland Monitoring System

"Those who cannot remember the past are condemned to repeat it." **Santayana 1905**

This chapter provides background information on the intellectual thought and technique development of rangeland monitoring in Western Australia and its eventual evolution into the current state-wide pastoral lands monitoring system. The current system is described. It is widely recognised for a number of intrinsic strengths including longevity, size and stable field protocol incorporating a suite of simple, robust techniques but it has shortcomings which are also described.

3.1 Introduction and Philosophical Background to Monitoring

From its beginning, pastoral rangeland management, natural resource assessment and monitoring in Australia has been closely tied to the needs of domestic or managed livestock grazing on native vegetation. The techniques developed in Western Australia, although influenced by the theory and practices of range condition assessment established during the 1930s and 40s in the United States (US) by federal agencies such as the Forest Service (USFS), Bureau of Land Management (BLM) and the Soil Conservation Service (SCS), differed markedly in application and philosophical approach. In the US, the focus of most of the early rangeland managers and scientists was on the production of high quality livestock forage (National Research Council 1994, p57), in particular, the portion of the vegetation community that comprised livestock forage (West 2003), and by 1950 was quantified or assessed as range condition, benchmarked against a desired plant community or climax composition, using vegetation succession-regression theory.

In contrast, in Australia and particularly in Western Australia, the early assessment philosophy embraced (and still does) a stronger focus on the maintenance of the integrity of natural rangeland ecosystems, based on the detection of *change* in vegetation and soil condition (Hacker 1992). The major reason for the philosophical and practical differences between Australia and the US is due to the considerably more variable climatic conditions experienced in Australia and therefore more marked seasonal variations. As Lamacraft (1978) states, *"Attempts to transfer American methods to our rangelands have proved lacking…"* principally because of our erratic rainfall and its effect on the vegetation. Essentially, Australian rangeland scientists set out to measure attributes that they thought important based on local experience, rather than relying entirely on contemporary US ecological theory such as the Clementsian and Quantitative Climax theories. Lamacraft (1978) also makes the important point that Australian techniques must handle sequences of drought years when shrubs are the only plants present, that is, lacking forbs, annuals and grasses.

Holm, Burnside & Mitchell (1987) provide a succinct and thought-provoking discussion of the objective of rangeland management in Western Australia, including the role of monitoring and the requirements of a monitoring system. The discussion revolves around the issue of whether rangeland management should be focussed on maximising grazing animal production or on the apparently contradictory focus of retaining the land in pre-grazed (by introduced stock) condition. They conclude that the objective should be to maintain shrubland vegetation in its natural balance of palatable and less palatable shrubs, and that this is indeed compatible with maximising sustained animal production from a particular area.

An important implication arises from this conclusion. It is that rangeland monitoring should capture both ecological and pastoral production attributes, including the assessment of soil stability and health. Healthy soil is a fundamental necessity for all natural resource land uses.

3.2 History of Pastoralism in Western Australia

Very soon after European settlement in eastern Australia, it was recognised that the grazing of sheep and cattle could be financially lucrative and hence was pursued with considerable enthusiasm, albeit not always by people with suitable experience and environmental integrity or wisdom. The early years of pastoralism in Australia were restricted to the naturally and reliably watered parts of the country, mainly along river systems, so called 'frontage country', and in the vicinity of springs and soaks. With very few natural surface waters in the arid and semi-arid rangelands, it was not until the advent of suitable water boring technology, principally cable tool drilling rigs in the 1840s (McGoggan 1997) and later dam-building machines such as the 'Tumbling Tommy' (Bennett 1997), that pastoralism was able to advance into these areas during the 1870s, 80s and 90s. These innovations were followed by other technological developments such as wire fences and steam engines in the very early 1900s, motorised transport in the 1910s, the Royal Flying Doctor Service (RFDS) 'mantle of safety' in 1935, and a host of innovations beginning in the mid-1900s (McKeon *et al.* 2004).

By the time Western Australia was founded in 1829, pastoralism was already well established in New South Wales and Queensland. In the southern rangelands of Western Australia, pastoralists generally followed in the tracks of the explorers, surveyors and prospectors, utilising their observations of suitable grazing lands. For example, the Geraldine Mine (lead-copper) was established in 1849 at Northampton, followed shortly after in 1850 by Geraldton town site and port approximately 50km to the south to service this mining enterprise. Whilst this was an important development in its own right for the young colony, the mining enterprise also drew public attention to the surrounding valuable pastoral country (Battye 1915). For example, Messrs. Burgess and Drummond, who had accompanied a contingent of soldiers to protect the miners from Aboriginal attack, took up pastoral leases in 1849 and 1850 and so became the pioneer pastoralists of the Victoria district (Battye 1915).

The mine served as a base for land exploration. From here, surveyor Austin in 1854 and explorer Gregory in 1858 each explored the Murchison and Gascoyne districts. Gregory's favourable reports of the pastoral potential encouraged others to take up grazing land in the lower Murchison and Gascoyne areas in the early 1860's (Battye 1915; Webb 1993). Pioneering pastoralist C. von Bibra took up land for sheep in the lower Gascoyne River area in September 1863. Others then steadily pushed eastward, initially along the Gascoyne and Murchison frontage country then into the poorly watered 'back country' using wells and bores to supply water (Webb 1993). It is worth noting that from the 1860s, the British Colonial Office stipulated that pastoral lessees must respect right of access to land for Aboriginal people for traditional activities (Webb 1993).

In 1863, Lefroy's survey party reported good pastoral country, although lacking surface water, in the Coolgardie area, but it was not until gold was discovered at Coolgardie in 1892 and Kalgoorlie the following year, that pastoralism began in the Eastern Goldfields. Newcomers soon realised the rich grazing value of the native bluebush *(Maireana* spp.) and saltbush *(Atriplex* spp.) shrublands, and by 1930 all of the chenopod country between Norseman in the south and Leonora and Laverton in the north had been taken up, usually in large pastoral leases (Ross 1991). In this region, it was by about 1920 that the pastoral industry had become independent of the needs of the local mining industry (Burnside 1991; cited in Ross 1991).

The familiar pattern of pastoralists following prospectors also occurred in the upper Murchison region. The Murchison and East Murchison Goldfields were proclaimed in 1891 and 1895, respectively, with pastoral development following soon after.

By the very early 1900s, much of the pastoral industry in the shrublands was underpinned by exploitation of artesian and non-artesian groundwater supplies. Very large flocks and herds of livestock were maintained in the arid interior from the 1890s through most of 1900s peaking in the early 1930s (Williams, Suijdendorp & Wilcox 1980), supported by a large and expanding network of artificial water points. This fundamental change from water-limited to forage-limited pastoralism was probably 'bad news' for most rangeland ecosystems. Unfortunately, the scientific evidence to properly substantiate and characterise this proposition is deficient, largely because the 'hoofed' advance was not ecologically monitored until relatively recently, well after the land degradation of the 1890s to 1930s. This early degradation was probably the most severe to occur in the entire 170 year pastoral history of Western Australia (Perry 1977; Noble 1979) but interestingly, in the Royal Commission report into the mid-1930s to early 1940s drought disaster (Fyfe 1940), there is no mention of 'land degradation' *per se* although there is discussion of dust storms - and apparently little recognition that permanent or long term ecological damage had occurred, and therefore no need for monitoring.

Monitoring did eventually commence, but only 55 years ago, spanning less than 35% of the industry's existence. Pastoral sheep production for wool and meat, along with some cattle raising and feral goat trapping continues in the Gascoyne, Murchison, Goldfields and Nullarbor regions but today few sheep are run north of the Carnarvon district, in contrast to former times when large numbers of sheep were run in the Pilbara and Kimberley regions.

3.3 Short History of Rangeland Monitoring in Western Australia

Rangeland monitoring in the broadest sense of an experiment designed to compare changes in vegetation over time commenced in Western Australian rangelands in 1951-52. During the subsequent 55-year period to now, there has been a steady evolution in monitoring philosophy and techniques. Based on monitoring objectives, three reasonably distinct phases or stages, each with different influences and incentives, can be recognised (Russell & Watson 2006). Each phase is described below in Sections 3.3.1, 3.3.2 and 3.3.3.

3.3.1 Early 1950s to Late 1960s

The first phase, which lasted about 20 years to the late 1960s, is characterised by the primary objective of developing an understanding of vegetation growth and response dynamics. This was done through the comparison of grazed and ungrazed areas, and the knowledge was quickly applied to helping pastoralists make ecologically better stocking rate decisions at the paddock scale, rather than having to rely solely on precedent stock numbers. Data on plants, including photographs, were collected from monitoring sites located outside and within exclosures (*pers. comm.* David Wilcox, Nov. 2005). David Wilcox, now an elder 'statesman' of Australian rangeland science, explains the background to this work. *"…the University of Western Australia (UWA) in association with the then Pastoralists Association and the George Aitken Pastoral Research Trust set up three exclosures on saltbush country on Barnong, Boolardy and Belele stations. The arrangement was that the pastoral companies would erect the fences and UWA would do the investigation with the assistance of the Department of Agriculture."* (*pers. comm.* David Wilcox, Nov. 2005).

This initial exclosure work, however, was engendered by some early ecological work on mulga *(Acacia aneura)* undertaken by George Melville (UWA) in the late 1930s on Boolardy station during a prolonged drought (the mid 1930s to early 1940s drought) and at the same time Reg Moir (UWA) was doing some similar work on Warralong station in the Pilbara. Nicholls (Professor of Agriculture, UWA) encouraged these studies in the rangelands until his departure, at which time interest waned. David Wilcox then continued with the exclosure measurements, initially during his post-graduate work at UWA and then from 1955 when he joined the Department of Agriculture Western Australia (*pers. comm.* David Wilcox, Nov. 2005). Interest by UWA fell away and the work was continued by the government.

David Wilcox was the first-appointed rangeland advisor in the Western Australia Department of Agriculture. In 1955, he commenced a partnership with Neil Mitchell of Barnong station to develop stocking rate decision strategies based on forage resource condition, rather than on historical paddock stock numbers. An important part of this strategy was the establishment of a suite of non-grazed benchmark exclosures with which to compare grazed areas (Mitchell, Mitchell & Alchin 2005). This was the first application of benchmark exclosures and photo points in the Western Australian rangelands.

Additional exclosures were set up by David Wilcox and others (including Geoff Lacy, Roger O'Farrell, Ron Hacker, John Lawson) during the late 1950s, 1960s and early 1970s on numerous stations including Belele (1956), Albion Downs (1956), Lyons River (late 1950s), Hillview (1959), Coodardy (1960), Koonamarra (1960), Edjudina (1961) and Gabyon (1965); a group of Gascoyne stations namely Mt Clare, Mt Sandiman, Cooralya, Dalgety Downs and Dairy Creek; Lake Mason (late 1960s) and Narndee (late 1960s or early 1970s). A variety of country types were sampled by these exclosures, installed in order to help answer specific ecological and grazing management questions. Information was then passed to the pastoralists at field days, which were generally well attended, and via Departmental publications such as the Rangeland Bulletin and, later, the Pastoral Memo (*pers. comm.* David Wilcox, Nov. 2005).

The Department of Agriculture Western Australia supported conscientious pastoralists through the 1960s with the use of fixed photo points and fenced benchmark exclosures, consistent with the strong Departmental extension focus on individual pastoral leases during this time. However, despite its usefulness, many pastoralists did not embrace this innovation. In the words of David Wilcox (*pers.*

comm., Nov. 2005) *"I don't think that the lessees used them except a very few of our converts. They were still in the mode of exploitation of the resource and not in its conservation and the word sustainability had not been 'invented' at the time."*

David Wilcox also undertook the first range condition and resource inventory survey in Western Australia at the instigation of the Pastoral Appraisement Board (now the Pastoral Lands Board). Commenced in 1969, the survey of the Gascoyne River catchment utilised for the first time in Western Australia the concept of rangeland types as the basis for mapping the distribution and severity of erosion in the catchment (Wilcox & McKinnon 1972). The rangeland type concept is very similar to the land systems concept practised by the CSIRO Division of Land Research in its surveys of land resources in other parts of Australia and in New Guinea at that time. In practice, there is little to distinguish the two; land systems have been used in all subsequent range surveys in Western Australia to the present day (2007). Interestingly, this first survey was commissioned by a concern about the increasing frequency of major floods in the lower reaches of the Gascoyne River, particularly affecting Carnarvon township and the horticultural hinterland, rather than interest in the condition of rangelands in the middle and upper parts of the catchment (Wilcox & Burnside 1994).

Significantly from an ecological point of view, the early monitoring and range survey work led to an appreciation that it is the condition of the perennial, rather than annual or biennial, component of the vegetation which is more closely related to the long-term health of the Western Australian rangelands (McKell & Goodin 1973; Moore 1973; Holm 1983; Watson 2002). Although the annual and biennial plants may contribute substantially to stock diet during good rainfall seasons, it is the perennial shrub component which contributes both feed and, more importantly, landscape stability during the usual dry seasons, particularly during prolonged droughts (Holm 1983) and post-drought recovery. This knowledge has since underpinned all of the monitoring techniques developed in Western Australia.

3.3.2 Early 1970s to Late 1980s

The second phase, which also lasted about 20 years, is characterised by a shift towards the provision of systematic broad-scale range condition and trend information to land administrators, as well as continuing to provide information at the station and paddock scale to pastoralists. This was a busy, exciting period of innovation. Three strong influences are evident: (1) a series of rangeland conferences and workshops which engendered strong enthusiasm for monitoring, (2) the need to establish systematic monitoring of the Gascoyne and Ashburton catchments following the devastating 1961 flood, and (3) an increasing national public desire to better manage the environment and natural resources.

Renewed interest in establishing systematic monitoring networks swept across the Australian rangelands in the late 1960s and early 1970s (Watson & Novelly 2004). This resurgence was part of a compelling national advance in thinking about the management of natural resources. Prior to this, attitudes in the Gascoyne River catchment failed to acknowledge the severe and widespread land or resource degradation as a result of overstocking, but attributed it instead solely to the severe mid-1930s (1935/36 – 1941) drought (Watson 2003 and references cited therein). Similar attitudes amongst pastoralists prevailed elsewhere. For example, further south in the Morawa area, pastoralists failed to link grazing pressure and resource degradation. These attitudes persisted up until the 1950s (Mitchell, Mitchell & Alchin 2005).

As part of the new national landcare awareness and global desire to ‘go forth and monitor’, the initiation of systematic rangeland monitoring in Australia can be traced to two principal ‘drivers’. The first relates to several conference workshops in the early 1970s. The first of these conferences, the Workshop of the United States-Australia Rangelands Panel, was held at Berkeley, California, in early 1971 (Anon.

1974). David Wilcox (Department of Agriculture Western Australia) attended this workshop, participated in discussions on range management and also presented a conference paper on the morphogenesis of woody plants (Wilcox 1974). The inaugural workshop was followed by a second workshop in Adelaide, South Australia in 1972 (Anon. 1977), a third in 1973 in Tucson, Arizona (Anon. 1973), a fourth in Alice Springs, Northern Territory in 1974 (Anon. 1979) and the last in Boise, Idaho in 1975. At the fourth Panel workshop, which had as its theme "Rangeland ecosystem evaluation and management", numerous papers were presented on such topics as the kinds of information and methods required for rangeland inventories and condition assessments. These Panel workshops arose from a 1968 agreement between the United States and Australian governments relating to scientific and technical cooperation. The US-Australia Rangeland Panel of about 30 scientists, established to promote cooperation in rangeland sciences, was very successful.

In addition to the US-Australia Rangelands Panel workshops, the Fowlers Gap (western New South Wales) workshop in 1973, held under the auspices of the Soil Conservation Service of New South Wales, was also an important intellectual 'milestone' in the development of range condition assessment. Around this time, Cunningham (1976), Noble (1979) and others were urging the importance of including soil stability in range condition assessments. Cunningham (1976) even proposed dropping the term 'range condition' because of connotations inherited from the US pertaining to animal production. Later in the decade, the first International Rangelands Congress (Anon. 1978) was held in Denver, Colorado in 1978 under the auspices of the Society for Range Management and a second held six years later in 1984 in Adelaide (Anon. 1986).

The overall effect of the 1970s conferences was to promote the desire amongst Australian rangeland scientists 'to get on top of the range condition assessment problem', using, in part, the major advances in US rangeland science made in previous decades and presented at these conferences.

The second direct driver or stimulus for range monitoring in Western Australia was provided by the Western Australian government. In a shift from intuitive decision making based on subjective and anecdotal information, rangeland administrators recognised the necessity, importance and value of using scientifically based data on resource condition in making decisions. In 1973, the Rangeland Management Branch of the Department of Agriculture received a formal request from the Pastoral Appraisement Board (PAB) to establish systematic monitoring in the Gascoyne and Ashburton catchments. The Minister for Agriculture at the time had *"… resolved that deviations from agreed stock numbers could only be approved if supported by evidence of change in the condition of the property concerned" (Holm 1983, p.6).* This provided official imprimatur to the intellectual machinations, initial development and field deployment of monitoring techniques, outlined below. The significant change in government attitude, if not policy, is revealed by comparing the recommendations of the 1940 Royal Commission and the 1979 enquiry into the pastoral industry (Wilcox & Burnside 1994). Early monitoring systems were focussed on collecting data that related the impact of livestock grazing to productivity of native forage in the pastoral rangelands. The impetus for monitoring came from the need to characterise the resource, that is, the quantity and quality of perennial native shrub forage on which the southern rangelands pastoral industry is reliant, particularly after recognition of the widespread degradation from overgrazing in the Gascoyne River catchment (Williams, Suijdendorp & Wilcox 1980; Watson 2003) and other areas of Australia (McTainsh & Boughton 1993, p.12).

The ultimate aim, of course, was (and still is) to improve rangeland husbanding, in other words, to better balance stock numbers with resource capacity. But remarkably, as Watson & Novelly (2004) point out, the rangeland profession rapidly became engrossed in the minutiae of measurement techniques and implementation logistics before properly exploring the fundamental question of what type(s) of assessment system(s) would best meet the management needs of pastoralists, responsible state agencies and other stakeholders. Indeed, from the review of range trend assessment conducted by Alec Holm (Department of Agriculture Western Australia) in 1983, it appears that a single monitoring system was expected to provide the 'answers' for a range of needs from the very local (paddock/leasehold) scale to the regional land administration scale (Holm 1983). Nevertheless, this early work, which included the development of measurement techniques (described below), was driven by growing global and local awareness of the adverse effects of ecologically inappropriate land use (not only in the rangelands) and provided a sound basis for future range monitoring in Western Australia.

Pastoral rangeland monitoring in Western Australia (and other states) is now embedded in the National Rangeland Monitoring Programme, originally proposed at the 5th Australian Soil Conservation Conference (Roberts 1992).

3.3.2.1 *Prototype Monitoring Techniques*

The current pastoral zone monitoring system, known as the Western Australian Rangeland Monitoring System (WARMS), grew out of several early precursor and prototype monitoring techniques. These are described below, and whilst one may get the impression of a plethora of techniques, the 'trial and error' or 'learn by doing' nature of development engendered an improvement in the understanding of rangeland landscapes and the appropriate techniques to assess change in pastoral or range condition (Holm 1993a).

(i) *Low-level Aerial Photography*

The first systematic monitoring undertaken in the Western Australian rangelands utilised low-level aerial photography. This application was an Australian first and commenced in 1970 through collaboration between the Department of Agriculture Western Australia and David Carneggie (University of California) (Carneggie, Wilcox & Hacker 1971).

Sequences of colour and colour-infrared aerial photographs were taken along predetermined, permanent ground-marked flight lines at approximately 500 ft (152 m) above the ground. The photographs were taken with 70mm Ektachrome aerographic film in a 70mm aerial reconnaissance camera fitted to a Cessna 182 aircraft (Morrissey 1976). About 142 flight lines (not including the initial experimental lines), marked with white-painted vehicle tyres, were installed on 50 pastoral properties in the shrublands over the next 10 years, mainly in the Gascoyne and Ashburton River catchments (Holm 1993c), but also in the Meekatharra and Kalgoorlie regions between 1976 and 1980. Aerial photographic monitoring sites and photography dates are listed by (Holm 1993b, Appendix 1, Table 1.1). Ground sites consisted of five contiguous plots of 20 x 30m with an aggregate area of 0.3ha (20 x 150m). Each aerial photograph covers one plot and a sequence of five photographs covers the flight-line site. The scale of the plot on the photograph was approximately 1:200. Each plant canopy outline and species name was annotated on clear overlays in the field. Cover was later estimated by dot-scoring using a dot-grid (see Box 3.1) under low magnification on a desk stereoscope.

The technique became known as the *flight line technique.* However, whilst not able to deliver the key objective of accurate measures of perennial plant density and foliar cover, the technique did provide some encouragement for range condition trend assessment (Holm 1983; Holm 1993c;a). The requirement to determine catchment-scale range condition trends, and hence to derive appropriate stocking rates, was not realised (Holm 1993c), mainly because of intrinsic technical limitations. The technique was discontinued in 1988.

The several shortcomings and limitations of this technique included the aircraft high operating cost, resulting in a total acquisition cost of $11 per photograph (1976 dollars) and its suitability only for open plant communities (density less than 2,000 plants/ha). Other interpretative difficulties included shadows obscuring plants (not all sites could be flown at midday), seasonal vegetation differences and other differences captured by photographs taken at different times of the year, and the very tedious method of cover estimation (see Box 3.1 below). Difficulty of marking-up photographs of timbered country was compounded by shadow, which varied between photographs with time of day and season, thus rendering portions unmarkable, resulting in common areas to be compared being reduced with each re-photographing.

There were also considerable difficulties in photograph acquisition, mainly in locating the flight line monitoring site (pre-GPS technology) and then keeping the aircraft flying parallel to and directly over the site centre line whilst minimising yaw, particularly in strong crosswind conditions. Jim Addison, a technical officer with the Department of Agriculture who was involved with the technique, provided the following insight to the difficulties; *"The pilot was unable to view the flight line once close. The camera operator (sitting behind the pilot) navigated and directed the pilot. This was facilitated by the use of a modified door, which gave some forward visibility and some capacity to target the centre of the flight line. This was done by looking down through a hole in the door to a piece of fencing wire attached to the fuselage and lining this up with the target. Navigation instruction to the pilot was through tapping either his right or left shoulder to indicate direction required. Savage cross-winds (especially on the Nullarbor) made for interest. Voice contact was not possible because of engine noise and the fact that the modified door caused the stall warning to go off intermittently. Trying to recover one's heart from* *amongst second hand breakfast (in the bottom of a hat) was an additional challenge."* (Jim Addison, *pers. comm.* May 2005).

BOX 3.1 *FLIGHT LINE TECHNIQUE COVER ESTIMATION*

Cover estimates are calculated using a 36-dot/cm^2 dot grid.
The grid is placed on the annotated plant outline overlay prepared from the aerial photograph.

Cover is calculated for each species using the following formula:
***% Cover = (∑dots within plant outline + ½∑ dots on outline / ∑dots per plot) x* 100.**

Dot scoring is carried out using low magnification on the desk stereoscope.

Information from undated sheet prepared by John Morrissey, found with archived Sturt Meadows aerial photographs taken in 1978 and annotated in August 1983.

Despite the limited spatial resolution of the aerial photographs, an important advantage of this technique is the relatively large 'sample size' compared to the later ground photographic techniques, described below. Holm (1983) provides a more detailed description of site setup and requirements, and an evaluation of the technique. The flight lines remain largely in place, but do not form part of the current WARMS (Watson & Novelly 2004). Whilst no attempt has been made in Western Australia to improve the technique through the adoption of modern navigation and digital photography techniques, research on the application of low-level digital videography is being undertaken in the Northern Territory (Bastin *et al.* 2002; Bastin *et al.* 2004).

In 1973, almost contemporaneously with development of the flight line technique, two other ground-based techniques were developed by officers of the Department of Agriculture Western Australia. John Morrissey developed a density sampling technique involving the assessment of vegetation and soil condition, colloquially called the 'Meekatharra Waltz' and Ron Hacker developed what Holm (1983) termed 'an ecologically-based technique'.

(ii) Morrissey Density Sampling and Soil Condition Technique ('Meekatharra Waltz')

Fixed monitoring sites were positioned at various distances from watering points according to specific criteria for pasture type (saline/non-saline) and stock water salinity, ranging from ½ mile (0.8km) to $1^1/_2$ mile (2.4km) (see Hacker 1973, p.14 for criteria). At each monitoring site, the technique involved measuring the density of selected indicator plants and a soil surface condition assessment.

Selected plants consisted of two or three desirable (decreaser), one or two intermediate and one or two undesirable (increaser) indicator species. Density was estimated by measuring the distance to the nearest individual of each of the indicator species at 10 randomly positioned sample points. Values were calculated for each class of indicator species from which a site condition rating was derived (Hacker 1973; Holm 1983). The method for random positioning of sample points, calculation of indicator values and site condition is described in Box 3.2 below.

BOX 3.2 ***'MEEKATHARRA WALTZ' METHOD FOR POSITIONING SAMPLE POINTS, INDICATOR PLANT DENSITY CALCULATION AND SITE CONDITION CLASSIFICATION (FROM HACKER 1973, P.14-15).***

1. *Using a relocatable starting point, locate 10 points at 40 pace intervals. Direction paced between successive points follows a sequence of random numbers (from supplied table); the number code is: 1-NE, 2-E, 3-SE, 4-S, 5-SW, 6-W, 7-NW and 8-N. Any direction reciprocal to previous direction to be discarded. The point is marked by a steel welding rod.*
2. *At each point, distance to nearest individual in each indicator class is measured to nearest metre. This figure then subtracted from 20 and the answer (score) recorded with species name; plants located beyond 20 metres recorded as zero.*
3. *Calculate average score for each indicator class (desirable, intermediate, undesirable) at each sample point. The indicator class average score is then divided by the number of species used in each class to give an* ***indicator value.***
4. *Site Condition Indicator: each class indicator value is then converted to a* ***site condition rating*** *(good, moderate, poor) compared to standard [reference] sites, using a density versus indicator value curve (supplied).*

Soil assessment comprised an 'area-class' soil surface condition index. The index is based on seven erosional disturbance classes (with subclasses) ranging from (1) "Nil surface disturbance" to (7) "Gullying and hummocking > 12 inches" (Holm 1983 Appendix 2, Table 2.3).

To complete the assessment, a black and white polaroid photograph was taken, ensuring that the relocatable starting point was included and marked.

This technique is well documented by Hacker (1973), who also includes an evaluation by his Department of Agriculture peers. The evaluation covered the following criteria: repeatability, simplicity, flexibility, sensitivity, bias, cost, input data, soil class and acceptability. In summary, the evaluation found a high level of acceptability by users, with its strengths being reasonable degree of repeatability (subject to some qualifications), low bias, simplicity and low cost. Its weaknesses included lack of flexibility, particularly in dense vegetation, simplistic and inadequate description of erosion, and large amount of input data. Sensitivity to detecting change was not determined.
The Morrissey 'Meekatharra Waltz' monitoring technique was not adopted by the Department of Agriculture Western Australia for routine or systematic application.

(iii) *Hacker DQC-based range condition technique*
This monitoring system is a modification of the Dyksterhuis Quantitative Climax (DQC) method (see Lendon & Lamacraft 1976, for an explanation) of range condition assessment and consisted of derived indices for botanical composition, density and growth-vigour of plants at monitoring sites, compared with plants within nearby exclosure benchmark sites (Hacker 1973). Additionally, separate indices of soil erosion by wind and by water were derived from the percentage area affected in each of a range of defined erosion classes (Holm 1983; Holm 1993c).

Further details on the vegetative phase index calculations are provided in Box 3.3 below.

BOX 3.3 ***HACKER DQC RANGE CONDITION ASSESSMENT: VEGETATIVE PHASE CALCULATIONS***

The following calculation steps are facilitated by a pro-forma work sheet provided as part of the method.

1. *The composition, density and growth vigour indices are calculated for each vegetation stratum - lower, middle, upper storeys – defined in Hacker (1973).*
2. *Composition Index is the proportion (%) of monitoring site biomass which represents pristine (benchmark) vegetation. Two stage calculation:*
    a. *Relative biomass (%): estimate % contribution of each species class (increasers, decreasers, invaders) to each stratum biomass.*
    b. *Composition Index (%): compare % composition of each stratum with Allowable Climax % composition; calculate the Composition Index.*
3. *Density Index is the relative stand density of increasers and decreasers, in each stratum.*
4. *Vigour Index is calculated for increasers and decreasers, in each stratum, according to definitions provided (Hacker 1973, p.26).*
5. *Stratum Index is calculated for each stratum, by summing the composition, density and vigour indices.*
6. *Vegetation Condition Index is calculated by summing the stratum indices.*

The Vegetation Condition Index then becomes the first part of a three-number Range Condition Score, the other two numbers being the water and wind erosion indices. E.g. 270/34/42.

These instructions are an abridged version of the more detailed instructions provided in Hacker (1973).

The eight type-intensity combinations for wind erosion, subdivided into six rating classes, ranged from (1) “No accelerated erosion” (index rating 50) to (8) “General surface movement with formation of shifting dunes” (index rating 0). The 17 type-intensity combinations for water erosion were subdivided into six rating classes; classes ranged from (1) “No accelerated erosion” (index rating 50) to (17) “Gullying very deep and extensive” (index rating 0). This index estimate is for the monitoring site as a whole. The type-intensity ratings for describing soil erosion are fully listed by Holm (1983, Appendix 2, Tables 2.1 and 2.2) and Hacker (1973, p.25 & 27). Box 3.4 below provides further details on the calculation of the erosion indices.

BOX 3.4 ***HACKER DQC RANGE CONDITION ASSESSMENT: SOIL PHASE CALCULATIONS***

A pro-forma work sheet and definition tables, provided as part of the method, facilitate the following calculation steps.

1. *Same procedure is followed for both water and wind erosion index calculations.*
2. *Estimate proportion (%) of soil surface not affected by erosion of any type.*
3. *Using the type/intensity erosion definition tables (Hacker 1973, p.25 & 27), estimate the proportion of soil surface affected by each water erosion types (1 to 17) and wind (1 to 8).*
4. *Calculate Water and Wind Erosion Indices according to the formula:*
   Index = (50 x % unaffected area) + Σ_n (Erosion type-intensity rating x % area affected) for n number of type-intensity ratings.

The Water and Wind Indices then become the second and third parts (respectively) of a three-number Range Condition Score. E.g. 270/34/42.

This technique is also well documented by Hacker (1973); who again includes an evaluation by his Department of Agriculture peers. In summary, the evaluation found, using the same criteria as used for the 'Meekatharra Waltz' technique, that its strengths were simple operation (although the pro-forma work sheets need simplifying), flexibility of use in a variety of rangeland types and conditions (except in very poor sites), repeatability of vegetative phase indices and low operational cost (perhaps offset by higher operator training requirements). Its weaknesses included poor repeatability of the soil erosion phase indices, and the potential for subjective bias introduced by different operators. Holm (1983, p.19) makes the additional comment that *"…systems which differentiate water and wind erosion are in many cases difficult to use."*

The Hacker DQC-based system was not adopted by the Department of Agriculture Western Australia for routine or systematic monitoring, and a suitable soil erosion assessment method, readily acknowledged as an essential part of range condition and trend assessment, had still not been developed by this time (Hacker 1973).

(iv) *HMW technique*

Following the two previous individual efforts, a more comprehensive ground-monitoring technique was commenced in 1973 by combining the strengths of the Hacker and Morrissey techniques. A preliminary description of this technique, developed at the 1973 Rangeland Management Conference (Department of Agriculture Western Australia), is provided by Hacker (1973, p.30). It was hoped that it would be ready for routine field use by mid-1974. Importantly, the WA rangeland scientists envisaged at the time that benchmark exclosures would be set up in each vegetation type throughout the southern rangelands. The new technique became known as the Hacker-Morrissey-Wilcox (HMW) technique (Holm 1983).

Monitoring site selection was loosely addressed by the HMW technique such that each 5 ha monitoring site was located within a particular rangeland type, set at a distance from a water point according to water salinity (closer for higher salinity water) and principal pasture type (Holm 1983).

The technique, in which the density of selected plant species was estimated by a nearest-neighbour method (mean plant-to-point distance from twenty fixed points, increased from the original 10 points used in Morrissey's 'Meekatharra Waltz'), was designed for population sampling of randomly dispersed individuals (Strickler & Stearns 1963). Similar to the Morrissey technique, the selected plants at each monitoring site comprised two or three desirable (decreaser), intermediate and undesirable (increaser) indicator species. Density indices for each indicator class were then calculated from the distance measurements.

In addition, the vigour of each of the desirable species (but not intermediates or undesirables) was assessed (good, fair, poor) and an overall site vigour index derived. Finally, to complete the vegetation assessment, the proportional cover (%) of annual species was estimated (Holm 1983).

Soil assessment was carried out on the same twenty fixed points used for the plant density sampling plus an additional twenty points, using a 'type-intensity' index based on five classes ranging from (1) "No accelerated erosion; abundant cryptogams" to (5) "Area almost completely scalded; extensive gully systems" (abbreviated description) (Holm 1983, Appendix 2, Table 2.4) The index is calculated on the proportion (%) of sites in each disturbance class, similar to the calculation in the Hacker DQC soil phase technique.

Finally, a photographic record of the site completed the field assessment. Further details on setup requirements are provided by Holm (1983, pp.8-10).

The technique was trialled between 1974 and 1978, but was found to be very time consuming, particularly in sparse vegetation, and the relocation of permanent marker pegs difficult (Holm 1983). An appraisal undertaken by Holm (1983) found, among other shortcomings, that plant density estimates were inaccurate due to an insufficient number of sample points (20).

In a comparison of the HMW technique and the earlier developed flight line technique undertaken by Don Burnside (Department of Agriculture Western Australia) (Holm 1983, Appendix 3), there were marked differences in absolute plant density (plants/ha) estimates, but reasonably similar estimates of relative density or density change (± % change) between the two sample years (1975/76 and 1978) for about five of the nine pastoral leases used in the appraisal. The percentage change in the density of the three classes of plants (desirable, intermediate, undesirable), having both a direction or trend (negative, positive or neutral) and a magnitude of change (absolute value), is termed range trend in this comparison. The statistical correlation (Pearson Rank) between density changes (all plant classes) for the two techniques is 0.517 ($p = 0.006$) [regression and correlation analysis by P. J. Russell unpublished]. On a general note, it is interesting to reflect that both techniques

(HMW and flight line) showed that the plant density change, that is, the so called 'range trend' for the desirable (decreaser) plants from 1975/76 to 1978, was negative (declining) for the majority of leases used in the appraisal.

The HMW technique was found to be too time-consuming for the limited data captured, and was not adopted for routine or systematic monitoring by the Department of Agriculture Western Australia (Holm 1983). It was not made operational and is not part of the current WARMS. However, the strong desire to include soil condition assessment in rangeland natural resource monitoring was carried forward. A more advanced method for soil condition assessment is now an integral part the current WARMS protocol. The protocol, including development of the soil condition assessment technique, is outlined later.

(v) *Ground photographic technique*

A fourth ground-based technique was also developed in the 1970s, termed the ground photographic technique. A variant of this technique is incorporated in the current WARMS protocol. The technique was developed by John Morrissey (Department of Agriculture Western Australia) in 1975 (Morrissey 1976) as a direct aid for pastoralists. It consisted of oblique, 35mm photographs of fixed sites or plots taken with a handheld camera from a fixed photo point. This technique is similar to but more prescribed than that used by Wilcox in the late 1960s-early 70s in exclosures (discussed earlier). Each site is marked by two numbered reference pegs (steel star-pickets) 1.2m high, set 10m apart (changed to 13.5m in new WARMS) along the axis of the photo site. The camera position is 3m above the ground and 12m from the front reference peg, aligned so that the horizontal top edge of the picture frame forms a "T" with the rear reference peg. All perennial plants visible on the photographic print, within the field-of-view between the base of the rear (back) peg and the bottom of the photograph (foreground), are individually outlined, identified and counted on a clear overlay. The area covered by the photograph was just over 0.02 ha. A second photograph providing a general landscape view to the horizon was also taken.

In due course, it was found that the photographic print-edge was an unsatisfactory demarcation due to photo-cropping variations during printing (Holm 1983). To overcome this difficulty, photo sites were pegged on the ground to demarcate a trapezoid-shaped area (to account for the perspective effect). The dimensions, 15m wide at the rear, 4.3m at the front and 15m deep, define an area of 154.4m^2 (Layout A) (Holm 1983) were simply determined from the field-of-view of a photograph taken with a 35mm (format) camera and standard 50mm (focal length) lens, set 12m away from the front reference peg.

After a number of years of regular use, the two-photograph and Layout A field protocol was changed in 1982 to a one-photograph and modified photo site dimensions (Layout B) protocol. The new dimensions are 13.0m wide at the rear, 5.0m wide at the front and 13.5m deep, defining an area of 121.5m^2 (Holm 1983). The front and rear reference pegs are thus 13.5 m apart. The single photograph is taken 8.5m (not 12m) from the front reference peg at a height of 3m (same as for Layout A) to include the demarcated area and as much of the background as possible (Holm 1983). A panoramic view of Layout B is shown in Plate 3.1. This layout protocol is now standard for current WARMS sites.

PLATE 3.1 Panoramic view of an early WARMS monitoring site, Sturt Meadows station, 1983, showing demarcated photosite (Layout B, standard for WARMS sites since 1982); note crouching person at rear of photosite. [Photographer not known; photograph source: DAFWA, Kalgoorlie, Range Monitoring Sites file (archived), Film Batch C739-83, negative # 21 and 23; digitally scanned and merged].

A key part of this technique from the start was the free provision of photographs in annotated albums to pastoralists. The pastoralist was the sole custodian of any information derived from these photographs. Indeed, in an apparent contradiction to the Departmental objective at the time of developing a monitoring network or system suitable for regional land administration (that is, data collated from many leases), John Morrissey (Department of Agriculture Western Australia) established agreements in the Goldfields whereby the data remained confidential to the lessee (*pers. comm.* Ian Watson, January 2006).

This is the Pastoralists' Photographic (Monitoring) System (PPS), which now complements current WARMS ('New WARMS'). A total of 469 sites were installed on 38 pastoral leases distributed through the Carnarvon, Meekatharra and Goldfields regions, between 1975 and 1982, including the initial trial sites on Credo and Mt Vetters stations (Kalgoorlie district); these sites are listed by (Holm 1983, Appendix 1, Table 1.2).

The rationale for using photographs was sound then, and remains so to this day. It was well recognised that *"the growth or decline of perennial plants or the development or decline of obvious symptoms of soil erosion can occur so slowly that the overall impression gained by people regularly observing the country is that the landscape is stable and unchanging" (Morrissey 1976, p.2)*. Time-sequenced photographs of fixed sites provide land managers with clear unbiased visual evidence of change over multi-year periods, upon which objective and better informed management decisions can be made in order to protect the productive capacity of the plants and soil. However, despite this and other strengths, the technique does have weaknesses as recognised by Holm (1983; 1993b). For example, in sparsely vegetated areas it is useful for assessing plant density but in moderately or more densely vegetated areas, the technique is unreliable due to the obscuring of some plants by others, and the time required for manual overlay annotation (photograph mark-up).

(vi) (Old) WARMS

By 1980, intellectual thought on rangeland monitoring, together with the accumulated practical field experience within the Department of Agriculture Western Australia on particular techniques, had developed to the extent that a more comprehensive, extensive and generally acceptable technique for monitoring or assessing regional range condition could be developed. The critical thought change was that monitoring sites would now be designated to provide data for both regional range condition assessments for government land administration agencies (not previously done), as well as provide local information to pastoralists, as was done with the previously described ground-monitoring techniques.

The new technique incorporated the cost-effective ground-photographic technique, the PPS (Pastoralists' Photographic System), to which were added fixed belt transects for the recording of plant metrics. Belt transects could be used in a wide variety of plant communities. The intention was to include comparisons between monitoring sites and exclosure (fenced) benchmark sites and water-distant, unfenced reference sites of the major vegetation communities so as to enable the relative effects of grazing and climate on plant changes to be elucidated (Holm 1993b).

The new technique, later named the Western Australian Range Monitoring System, now generally referred by its acronym as WARMS, was field trialled on Boolathana station near Carnarvon in 1980 and formally adopted by the Department of Agriculture Western Australia in July 1981 (Holm 1983 cited by Holm, Burnside & Mitchell 1987; Holm 1993c). Minor modifications were made in September 1982.

The stated objectives of WARMS at this time (Holm 1983) were:

a. To provide written and visual records of long-term changes in the vegetation and soil surface, and
b. To interpret these changes in relation to climate and management.

From repeated comparisons between range monitoring sites and associated benchmark sites, long-term changes or trend would reflect the suitability (or otherwise) of pastoral lease or stock management actions, and hence serve three main purposes (Holm 1983), namely:

(i) Assist the decision making of pastoral managers,
(ii) Assist government rangeland officers in understanding range trend ecological processes, and
(iii) To provide evidence of the wise use of pastoral land to government and community.

Each range monitoring site consisted of a standard photographic site (Layout B – see earlier text for description and Plate 3.1) and a series of permanently marked belt transects. The original design incorporated ten transects, each 2m in width and between 10 and 20m in length, in a fan pattern radiating from the rear photo-site reference marker peg. However, due to relocation and position description difficulty, the layout was soon modified such that several transects were laid out from the rear edge of the photo site, parallel to the photo-site centre line. According to the specifications (Holm 1983), the number of transects and the length and width of each was chosen so that at least 100 (preferably 200) perennial shrubs were 'captured'. For sparse communities, say less than 1,000 plants/ha, the maximum aggregate transect area was 2,000m^2.

The data collected on each transect comprised the following vegetation and soil attributes (Holm 1983, p.14):

(i) Total number of each perennial shrub species present, scored into two size classes (young/mature),
(ii) Foliar cover including perennial grass butts (>2.5cm diameter), by centre line intercept method,
(iii) Perennial shrub seedling density (Braun-Blanquet 1965 scale),
(iv) Annual species cover (Braun-Blanquet 1965 scale),
(v) Ranked degree of grazing of each perennial shrub species, and
(vi) Soil surface condition; separate indices for wind and water erosion.

(Holm 1983, p.15) provides details of the labour and material requirements for the setting up and re-assessment of range monitoring sites. By March 1983, 254 WARMS sites had been established on 13 pastoral leases in the Carnarvon and Meekatharra regions (Holm 1983 Appendix 1, Table 1.3).

As mentioned earlier, an integral part of the WARMS plan was the establishment of a network of fenced pasture benchmark sites throughout the rangelands, representative of the types of country monitored by the range sites. Belt transects within each benchmark site would be measured annually, utilising the same protocol as the range sites, and total seasonal rainfall would be recorded. Unfortunately, only three benchmark sites were established by March 1983 (Holm 1983).

In his preliminary review of WARMS after two years of operation, Holm (1983, p.15) provides some insight and comments. He notes that the data collected comprise both visual information (photographs) and reliable plant metrics, supplemented by unreliable soil condition descriptions. Overall, however, the technique is able to provide useful information to pastoralists and land administrators for most vegetation types and was thus considered to be cost-effective. Its minor drawbacks included some difficulty in dense and/or tall shrub communities and the determination of actual plant numbers for some basal resprouter species such as *Atriplex* *rhagodioides.* The lack of a suitable soil condition and erosion assessment method that could detect even moderate change was still a major weakness that was sorely felt at the time.

In late 1986, after 5 years of operation, a review of WARMS was initiated by Ron Hacker (Department of Agriculture Western Australia) (unpublished internal memo. to Don Burnside, 14 October 1986). Hacker states, *"experience with WARMS … has highlighted a number of deficiencies which need to be addressed if the data produced are to be interpretable in terms of cause and effect relationship, and are to be acceptable by pastoralists as a basis of management decision-making"*. The wide-ranging proposed practical improvements were related to monitoring site selection, clarification of the distinction between Class A and B sites (not the same distinction as Layouts A and B), recording of water salinity, reference and benchmark sites, site layout, transect dimensions, site photographs, photograph mark-up, criteria for measuring canopy dimension, application of the '30cm rule', abundance scoring, and, importantly, acknowledgement that soil surface condition classification continued to be the least robust part of the technique.

Class A and B sites were not to be distinguished solely on the basis of the density of desirable (decreaser) plant species. Rather, *"class A sites were to be installed where the density of the major species group exceeds 400 plants/ha and class B sites installed when there are insufficient plants of any type to justify data collection."* (Hacker 1986, p.1).

In regard to soil assessment, the existing technique was recognised as being too subjective, prone to operator error and to significant differences between operators on particular soils such as red earths and sandy soils. It was also recognised that the overall erosion type-intensity rating criteria were not very sensitive to change. Measures to improve soil surface assessment included better criteria of degraded soil surfaces, and the use of two-operator average assessments.

Hacker (1986) also raises the issue of plant utilisation. He states, *"…an index of grazing utilisation for each plant is considered essential as an aid in interpreting the likely role of grazing in determining the observed changes in plant populations"* and he considered that assessment of individual plants is superior to assessment of the site as a whole. Hacker proposed a two-part utilisation index – one part to reflect historical or long-term browsing and the second to reflect recent, short-term or current browsing. Each index would have a 3-tier scale, namely, "Nil-Light", "Moderate" and "Heavy", each tier defined by the browse effect on plant structure. Unfortunately, this very sound idea was not adopted, probably because of high between-operator error (*pers. comm.* Ian Watson, September 2005).

Thus, this second phase in the evolution of monitoring in Western Australia, from the early 1970s to the late 1980s, was a busy, exciting period of technique innovation, characterised by the provision of systematic broad-scale range condition and trend information to land administrators, as well as continuing to provide information at the station and paddock scale to pastoralists. Despite some shortcomings, this work provided a very sound basis for refinement of WARMS field techniques in the next phase.

3.3.3 Early 1990s to Present

In response to information demands from a broadening range of stakeholders and interested groups, WARMS was again reviewed by the Department of Agriculture Western Australia in 1992 from which substantial changes were yet again instigated (Holm 1993a). The changes occurred in two main areas, strategic and technical; however, most crucially, this current phase of monitoring is characterised by stability and standardisation of the WARMS field and database protocols.

The principal strategic change was the re-alignment of the system to provide only regional-scale information for government-related purposes. The provision of pastoral lease tactical or local-scale management information was discontinued (Watson & Novelly 2004). Many existing monitoring sites were 'dropped' from the formal WARMS monitoring programme and returned to the pastoralists for their own use as PPS sites. The first new sites, now termed 'New WARMS' sites, were installed in 1994 and the earlier installed WARMS sites (1981 – 1993) are termed 'Old WARMS' sites. The New WARMS objectives, standard field procedures, information products and other details are described in Section 3.4 below.

The principal technical improvements introduced at this time were (1) transect plant census, (2) Landscape Function Analysis (LFA) and (3) Normalised Difference Vegetation Index (NDVI). The census technique of sampling plants involves establishing the location of the base of every plant using a local transect-based Cartesian coordinate method. Each plant is assigned a 'longitude' (distance along transect from the start point) and a 'latitude' (right or left and offset distance from transect centreline). The immense strength of the census technique is that it allows the life history of individual plants to be followed and therefore population metrics and dynamics to be studied. Introduction of the census technique into the 'New WARMS' field protocol has an interesting and checkered history. It was first used in some exclosures in 1969/70 and on a number of research projects in the southern rangelands (by Gardiner at Yeelirrie station, Mitchell at Coodardy station, Fletcher at Yerilla station and Watson at Boolathana station) but was dropped from routine monitoring by Alec Holm (Department of Agriculture Western Australia) in the late 1970s or early 1980s before being re-introduced to 'New WARMS' from 1992. The main weakness of the census technique is the extra field time involved in measuring the location of all plants on newly established transects, and for newly established plants (recruits) on existing transects. However, its use in WARMS is very well-established as a core strength, the data-rich advantages easily outweighing the time penalty.

The development of landscape function and soil surface condition parameters by David Tongway on Boolathana station and elsewhere (Tongway & Greene 1989; Tongway 1990;1992) and their incorporation into the WARMS field protocol is another technical advance achieved early in this current monitoring phase. LFA (Landscape Function Analysis), the collective term for the parameters and derived indices, filled a major shortcoming in Western Australian (and Australian) rangeland monitoring that had existed for about 40 years despite concerted efforts by earlier workers to develop a suitable technique to quantify soil erosion and other soil surface features. A strength of the LFA technique is its foundation in arid zone ecosystem resource transfer-capture mechanisms. The mechanisms are explained in Chapters 2 (in the section describing ecological models) and 4 (in the section dealing with the development of an index of range condition).

The third technical improvement is the addition of Normalised Difference Vegetation Index (NDVI) data to the WARMS database. Values of NDVI, an estimation of vegetation greenness, are extracted from Thematic Mapper satellite observations for particular time periods and are available as time-series graphs. To date, little quantitative use has been made of this data, and it has not been used in this study.

In conclusion, there are two important aspects of field method evident in this examination of monitoring innovation in the Western Australian rangelands. Although a number of techniques were developed and trialled, mainly during the second phase (early 1970s to late 1980s) – see ‘Prototype Monitoring Techniques’ discussed earlier – each was designed, first, to be as uncomplicated as possible, and, second, to be suitable for all vegetation types and regions. In other words, there appears to have been a conscientious effort to develop a ‘one size fits all’ technique, rather than developing a range of modifications to suit specific vegetation types. Although this conservative approach exposes limitations in some situations, the merit is very clear – durable and consistent field measurement conventions which produce high quality data. This data is then comparable between regions and vegetation types, a strength that should not be underestimated.

3.4 The Contemporary Monitoring System (WARMS)

This section describes the current WARMS protocol for the southern rangelands of Western Australia. The revised and enhanced protocol, incorporating institutional and scientific monitoring objectives, site stratification, location criteria and field layout, was established following the major review in 1992 (Holm 1993b) and has been used for all WARMS sites installed from 1994 to the present. These are known as 'new WARMS' sites to differentiate them from the earlier ('old') WARMS sites. Most of the information in this section is sourced from Watson, Novelly & Thomas (in press), one of a trilogy of papers comprising the most recent and comprehensive review of WARMS.

3.4.1 WARMS Objectives

The overall objective of WARMS is to provide information on change in the pastoral rangelands. Although there is a wide range of potential users of this information, each with different objectives, most users interpret observed change in terms of range condition or trend, either from a pastoral productivity perspective or from an ecological perspective. Both perspectives can be compatible (Holm, Burnside & Mitchell 1987; Skelton & Skelton 2007), within the constraints of a ground-based point monitoring system.

More specifically, WARMS is designed to:

(i) Track long-term changes in vegetation and soil rather than ephemeral or seasonally-driven short-term changes,
(ii) Track ecological change rather than specific change in livestock-related condition or forage production,
(iii) Operate across all types of pastoral country and vegetation types,
(iv) Provide regional-scale information rather than information for individual leases, and
(v) Facilitate the development of causality cases for change, the principal causes being grazing and climatic conditions.

It is important to note that, in general, WARMS data cannot be used to undertake comparisons between current range condition and some pre-established set of reference or 'natural condition' sites. To do such an analysis would require the re-establishment or refurbishment of the (few) existing benchmark exclosures and the establishment of many more within representative vegetation types. Apart from the prohibitive cost, the main impediment to establishing more exclosures or reference sites is the difficulty of finding areas that have not been disturbed, that is, 'natural areas'.

3.4.2 Site stratification and Location Criteria

Following the 1992 WARMS review and the strategic decision to change from the provision of both lease-specific and regional information to the provision of regional information only, the number of sites required to meet the new objectives was determined by a process of stratification. Sites existing at the time (now termed 'old' WARMS sites') were taken into account. Site stratification involved four stages:

(i) Determination of total number of sites that could be included in the system,
(ii) Allocation of sites to broad vegetation groups,

(iii) Allocation of sites to individual pastoral leases, and
(iv) Application of local field criteria.

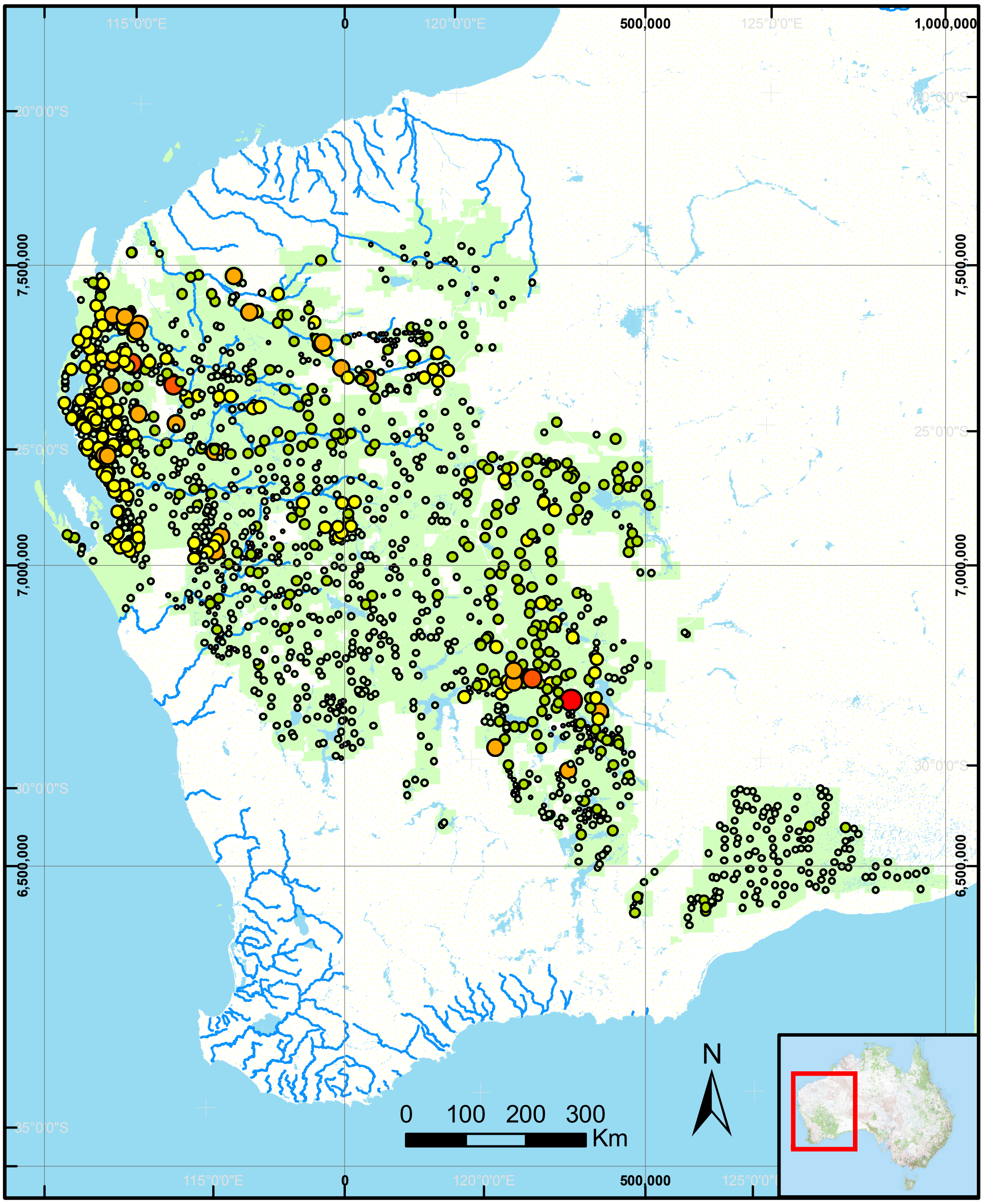
A total of approximately 1,240 sites was determined for the southern rangelands (380 for Kimberley) to be a reasonable compromise between an adequate density of sites for meaningful data capture and available institutional support (funding and staff). As at September 2006, 980 sites were active in the southern rangeland shrublands; the distribution is shown in Figure 3.1.

Seven broad vegetation groups, listed below, were defined for the southern rangelands (six for the Kimberley).

(i) (EB1) Spinifex grassland,
(ii) (EB3) Short bunchgrass savanna,
(iii) (EB4) Chenopod (saltbush and bluebush) shrubland,
(iv) (EB5) Other Acacia low woodland,
(v) (EB7) Eucalypt chenopod shrubland and woodland (Goldfields gum belt),
(vi) (EB9) Mulga shrubland and woodland, and
(vii) (EB10) Nullarbor (chenopod shrubland).

Sites were then allocated to vegetation groups using an index comprising a pastoral productivity rating (0-25 livestock equivalents/km^2), a fragility index (0-1.25) and areal extent of vegetation group (20,551-253,788 km^2). A multiplicative algorithm was used, thus an increase in productivity rating or fragility or areal extent had the effect of increasing the number of sites allocated to a particular vegetation group.

Western Australian Rangeland Monitoring System (WARMS)



Legend

Count of Field Assessments

- 1
- 2
- 3
- 4
- 5
- 6
- 7

Coordinate System: MGA 94 Zone 51

Southern Rangelands Site Location and Count of Field Assessments

1920 sites, assessed between Feb 1984 to Sept 2006

Peter Russell 12 September 2007

Figure 3.1

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

C:\SRCGIS\MapDocuments\WARMS_LocationAndCountOfFieldAssessments_MGAZ51_20070912.mxd

Consistent with the regional vegetation stratification, site allocation to individual leases in the southern rangelands was subject to the following two criteria:

(i) Maximum of 10 sites per lease,
(ii) Minimum of 2 sites per lease if lease >50km^2; sites were not installed on smaller leases.

At the local site scale, sites were installed according to the following field criteria:

(i) The complete range of vegetation condition states in each major vegetation group in the region to be sampled by groups of 10-20 sites; most sites were located within the most common state.

(ii) Sites located at least 1.5km from permanent water, except where water salinity exceeded 5000ppm total soluble salt, the minimum distance was reduced to 1km.

(iii) Sites to be located towards the centre of a larger (grazed) area of a particular vegetation group within each paddock.

(iv) Ensure ease of relocation and access, but not such that sites are affected by tracks and other infrastructure (usually 150-300m from fence lines and tracks).

(v) Not located in holding paddocks or other special use areas.

(vi) Not located on dynamic areas such as actively eroding land or in drainages.

(vii) Centre line of site to be aligned approximately parallel to maximum slope direction.

(viii) Old WARMS sites to be utilised if they meet the (new) stratification and location criteria.

3.4.3 Monitoring Site Layout

Site layout is shown in Figure 3.2 below. Each site is comprised of two contiguous parts:

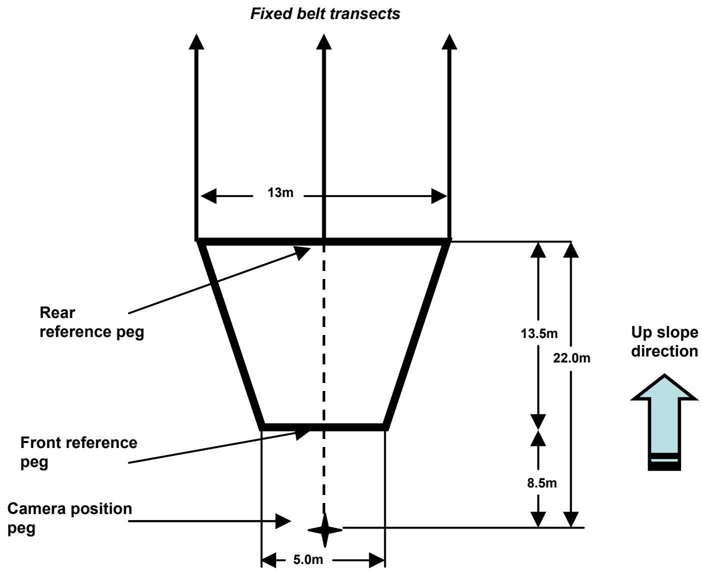


Figure 3.2 Standard layout of WARMS monitoring site showing the photosite (trapezoid) and transects for shrublands in the southern rangelands, Western Australia.

(i) A photosite (also known as a photoplot) consisting of a trapezoid-shaped area of 121.5m^2 delineated by permanent short galvanised-steel pegs located at the four corners and two reference pegs (front and rear) defining the site centre-line. The photosite is photographed from an elevated camera position (approximately 2.5m), on each occasion that a new set of transect data is collected. Photographs are stored in the WARMS database to provide a visual record of the site, complementing the quantitative transect data.

(ii) Three parallel belt-transects, 6.5m between mid-lines, are laid out from the rear of the photosite and marked with short permanent pegs at the end and mid-points. Transect dimensions depend on the density of the most common indicator shrub species at the site – see Table 3.1. The maximum aggregate transect area is 1,200m^2 but in low density plant assemblages, this may not be sufficient to sample the minimum 50 indicator plants.

Table 3.1 WARMS transect dimensions for southern rangeland shrubland sites (from Watson et al. 2007).

Density of most common indicator shrub species (plants/ha)*	Transect length x width (m)	Number of transects	Aggregate transect area (m^2)
400 – 1,000	100 x 4.0	3	1,200
1,000 – 2,000	100 x 2.0	3	600
2,000 – 4,000	50 x 2.0	3	300
4,000 – 8,000	50 x 1.0	3	150
8,000 – 20,000	50 x 0.5	3	75
>20,000	20 x 0.5	3	30

* 1,000 plants/ha = 1 plant/10m^2

The centre transect is used for LFA (Landscape Function Analysis) and SSC (Soil Surface Condition) assessments.

3.4.4 Attributes Captured

In the southern rangeland shrublands, attributes of soil-landscape and vegetation are captured at each WARMS site at approximately 5-year intervals.

The metrics recorded along each transect for each perennial plant include:

- Identification to species,
- Location (Cartesian coordinates with respect to transect start point),
- Size (height and maximum canopy extent).

Only perennial trees and shrubs, with lifespans exceeding 5-10 years, are recorded and the following measurement conventions are applied:

(i) Plants must be branched, ≥ 100mm high and basal stem diameter ≥ 4mm.
(ii) Plants taller than 200cm are recorded as 205cm,
(iii) The '30cm-rule' is applied to plant clumps to differentiate between individuals that have resprouted from a parent. A distance of ≥ 30cm between stems at ground level defines a different plant.

As each plant is recorded electronically it is given a unique identifier and cross-referenced with its location, which allows individual life histories to be determined and hence population parameters such as recruitment, survivorship and mortality rates may be calculated. This census technique is a particular strength of the WARMS data-capture protocol.

The suite of attributes for landscape function analysis (LFA) and soil surface condition (SSC) assessment, recorded from along one of the transects, is adopted directly from Tongway (1994) and, Tongway and Hindley (1995). Attributes are a combination of surrogate and direct measures of patch-scale ecosystem functioning in relation to the capture and retention of water and nutrients. These attributes and the derived indices are described in more detail in Chapter 4, in relation to the development of an overall index of ecological health.

3.5 Limitations of WARMS for Monitoring Range Condition or Ecological Health

The purpose of this section is to provide an overview of the intrinsic limitations or shortcomings of WARMS for long-term monitoring of range condition or ecological health. The main reason for this discussion is to articulate important implications or caveats when reviewing results or interpretations derived from WARMS data, such as the research reported in later chapters. Some of the limitations are also addressed by Watson, Novelly and Thomas (in press).

WARMS is described in the previous section (Section 3.4). Apart from the low density of monitoring sites in the southern rangelands (average 1 site per 77,800ha), two fundamental characteristics severely constrain the ability of WARMS to provide comprehensive ecological health information; these are:

i. WARMS is a ground-based, point monitoring system, and

ii. Sites are mostly centrally located within stable, resilient or resistant parts of the landscape.

Clearly, WARMS does not provide complete spatial coverage of the landscape and it cannot be expected to do so. Given the high degree of heterogeneity or range of natural variation in arid landscapes, it is not possible for point-monitoring systems established under WARMS criteria to capture changes occurring in the intervening distance between sites until those changes impinge on the monitoring sites themselves. Hence, there is often a time lag in the detection of change. This fundamental characteristic is further exacerbated where sites are located within stable, slow-to-change parts of the landscape. When catchment-scale spatio-temporal hydrogeomorphic processes such as accelerated soil erosion, edaphic drying and vegetation homogenisation are considered, as has been recently done by Pringle *et al.* (2006), and in earlier studies Pringle (1998), Pringle (2004) and Pringle & Tinley (2003), it is clear that WARMS monitoring sites are only able to tell part of the total ecological story, are generally late in telling the story, and may miss much of the action.

Where is the 'action' likely to occur? The answer to this question is reasonably straightforward when patterns and processes of landscape succession are considered. A conceptual scale-dependent hierarchical framework as espoused by Pringle and Tinley (2003), is useful. Landscape succession is the natural process of landscape renewal – the erosion or stripping of old land surfaces and the formation of new surfaces – which operate at naturally balanced geomorphic rates of denudation. However, empirical evidence shows that anthropogenic activities frequently perturb the natural succession rate by altering (lowering) local drainage base-levels (often unintentionally) resulting in accelerated erosion by water (Tinley 1977; Tinley 1982; Tinley 1991). As incision (and lateral stripping) proceed at rates which are orders of magnitude greater than natural rates, an increasing amount of surface water is more rapidly drawn from the drainage interfluves to become entrained in zones of concentrated, higher-energy water flow ('alleys of concentrated drainage' – terminology of Pringle, Watson and Tinley (2006), rather than being able to spread slowly, pond or infiltrate.

Rangeland degradation is essentially a process of desiccation. Also known as edaphic drying or simply a drying change, desiccation results from reduced opportunity for surface water to infiltrate the land surface to recharge soil water stores. Thus 'the action' referred to above, that is, the impacts of accelerated erosion, is most evident in the areas of dynamic landscape succession such as along breakaway pediments, drainage tracts and on steeper slopes. It is in these areas that changes in vegetation, such as woody thickening or invasion, are likely to be most rapid. WARMS site location criteria specifically exclude such areas, strongly favouring the less active, more stable parts of the landscape, and hence WARMS sites are much less sensitive to changes occurring in the landscape.

Despite the severe limitation described above, there are two important positive messages and a note of caution. First, it follows from the probability of lag in the detection of change at WARMS sites, that if change (rather than no change) is detected at a particular site or group of sites, irrespective of whether the change is an improvement or a decline in range condition (or other attribute), then it might be inferred that the change occurred earlier and is more advanced in areas of active landscape succession, beyond the areas occupied by the WARMS sites. Therefore, detected changes from point-monitoring systems should not be ignored. If the change is undesirable (a value decision), perhaps indicating contraction of previously stable or intact areas, then the sooner follow-up investigation is begun and appropriate management action or remedial intervention is instigated, the better the long-term ecological outcome.

Second, WARMS is the only quantitative monitoring system present in the Western Australian rangelands and needs to be valued. It has already captured a large amount of valuable data, which over time and as new data are added will dramatically increase in value and utility. The caution is to not allow WARMS to be discarded; it is very beneficial. However, WARMS alone is not capable of answering important questions about the ecological health of critical parts of the landscape. The limitations of WARMS, inherent to all point-based systems, could be minimised if WARMS is used as the foundation of an enhanced monitoring system that incorporates other, more spatially extensive, catchment-scale hierarchical methods of data capture and analysis. This latter aspect, as important as it is, is not considered further here. The interested reader is referred to Pringle, Watson and Tinley (2006) and references cited therein.

3.6 Summary

From its beginning in Western Australia in the early 1950s, natural resource assessment and monitoring of the rangelands has been closely aligned to the needs of the pastoral industry. During this 55-year period, monitoring techniques and institutional objectives have evolved through three reasonably distinct phases.

The early assessment philosophy embraced (and still does) a strong focus on the maintenance of the integrity of natural rangeland ecosystems, based on the detection of *change* in vegetation and soil condition. An important finding from the early monitoring and range survey work was that it is the condition of the perennial, rather than annual or biennial component of the vegetation, which is more closely related to the long-term health of the Western Australian arid shrublands. In addition, although still not accepted by all pastoralists, recent ecological awareness recognises that maintenance of shrubland vegetation in its natural balance of palatable and less palatable shrubs is compatible with maximising sustainable livestock production from a particular area.

There are two important and persistent characteristics which thread through the development history of monitoring. First, efforts were directed at devising a single monitoring protocol suitable for capturing field data in all shrubland vegetation types and second, a single monitoring system or network was initially expected to provide the ‘answers’ for a variety of needs from the very local (paddock/leasehold) scale to the regional land administration scale. Whilst a single and robust protocol was eventually developed, the system was unable to adequately meet the day-to-day decision making needs of the pastoralists.

The new protocol, named the Western Australian Rangeland Monitoring System (WARMS), now generally referred to as WARMS, was field-trialled on Boolathana station near Carnarvon in 1980 and formally adopted by the Department of Agriculture Western Australia in July 1981. WARMS was reviewed in 1992, resulting in substantial upgrading of techniques and a major strategic change to provide only regional-scale information for government-related purposes. The principal technical improvements introduced at this time were (1) transect plant census, (2) Landscape Function Analysis (LFA) and (3) NDVI. The census technique is a core strength of WARMS, the data-rich advantages easily outweighing the field-time penalty. LFA filled a major shortcoming in Western Australian (and Australian) rangeland monitoring that had existed since the mid-1970s despite concerted efforts by earlier workers to develop a suitable technique to quantify soil stability and erosion. LFA is well founded in arid zone ecosystem resource transfer-capture mechanisms. The perennial plant metrics recorded along each transect include (i) Identification to species, (ii) Location of each plant and (iii) Size (height and maximum canopy extent).

The current phase of monitoring which began in 1993 is characterised by stability and standardisation of the WARMS field and database protocols. However, despite its considerable strengths, WARMS is a ground-based point (site) monitoring system, and therefore intrinsically not able to provide complete spatial coverage of the landscape.

Whilst WARMS monitoring sites are only able to tell part of the total ecological story, WARMS could be used as the solid foundation for an enhanced monitoring system that incorporates other, more spatially extensive, catchment-scale hierarchical methods of data capture and analysis. If this enhancement were to happen, it would mark the beginning of the next major evolutionary phase in rangeland monitoring in Western Australia, enabling the needs of a much wider range of interested stakeholders to be satisfied.

4 Development of the Shrubland Range Condition (SRC) Index

Chapter 4: Development of the Shrubland Range Condition (SRC) Index

4.1 Introduction

This chapter describes the indices developed as surrogates for various aspects of range condition or ecological integrity and their incorporation into a hierarchical index framework. Statistical relationships within the hierarchy are also examined. The resultant overall index, the Shrubland Range Condition Index, is then used in the next chapter to map patterns of change in the ecological integrity at WARMS sites throughout the southern rangelands.

The science of arid landscape ecology has advanced rapidly over the last two or three decades. A wealth of knowledge has been generated in Australia and elsewhere which is applicable to management of the rangelands in Western Australia. Rangelands comprise water-limited ecosystems, reliant on episodic and highly variable rainfall events. It is to these climatic conditions and to the nutrient-poor soils that the natural vegetation has adapted. The two main classes of plants, annuals and perennials each has a range of growth, reproductive and survival strategies to maximise the chances of population persistence. As mentioned earlier, it is the perennial plants which form the key structural and functional components of the ecosystems.

Superimposed on this natural order in Western Australia (and elsewhere) is a pastoral industry which is now forage-limited, not water-limited. The change occurred early in the occupation of the rangelands with the widespread development of artificial water points (see Chapter 3). The ungulate invasion and the large increase in Western Grey and Red kangaroo populations resulting from increased access to water, together with increases in the population of introduced herbivores (e.g. goats, camels, and donkeys) have collectively put enormous pressure on the native vegetation and soils through the imbalance created by the admixture of water-limited and forage-limited systems. It is the ecological health or condition of the vegetation and soils which concerns this study.

4.2 Development Objectives

The overall objective is to develop a robust quantitative index of ecological integrity that could be regularly calculated and mapped to show spatial and temporal variations or changes at WARMS monitoring sites, to help manage for long-term sustainability of the natural resource base. Indicators may not be able to predict changes, but must be able to highlight changes currently occurring and to rank their relative importance. An additional objective was to design a system which allows 'drill-down' from the overall condition index to the sub-indices to facilitate the building of causal cases for change. Thus the key features of this study are:

- a minimum and necessary suite of attributes in each of the three components of ecological integrity (structure, composition and function; see James (2004)), developed as indices to quantify each component.
- Hierarchical index framework with an overall index of ecological integrity. The index is termed the Shrubland Range Condition (SRC) Index to reflect that it was developed specifically for the southern, shrub-dominated rangelands of WA; adjustments would need to be made for use in grasslands, for example.
- The ability to track changes in the SRC Index and each of the sub-indices through time (time-slice technique).
- The use of GIS (Geographic Information System) techniques to map and analyse spatial and temporal patterns in the indices.

Table 4.1 (over page) lists the suite of indices developed and a short explanation of their use or indicator role. The principal constraint to developing a more comprehensive suite of indices was the limited number of vegetation attributes that are measured by WARMS. Only perennial plant attributes are measured; for each plant, they are:

- Location with respect to transect (georeference),
- Species,
- Height, and
- Maximum canopy width.

At first glance, it would appear to be a very limited set of vegetation attributes from which to develop ecological indices, however, several key aspects can be derived from this basic data and combined with a comprehensive suite of soil attributes, a very useful suite of indices has been developed.

Using the primary field captured metrics, a set of first and second-order indices were derived. These were then algorithmically combined (additive algorithm) to calculate third-order indices, each representative of a component of ecological integrity. The three indices, Landscape Function Factor (LFF), Vegetation Structure Factor (VSF) and Vegetation Composition Factor (VCF) were then algorithmically summed to calculate the overall index, the SRC Index. The hierarchical framework is shown in Figure 4.1. The component first and second-order indices are described below, as follows:

- Soil Surface Condition (Section 4.3),
- Landscape Function Factor (Section 4.4),
- Vegetation Composition Factor (Section 4.5), and
- Vegetation Structure Factor (Section 4.6)

Following the index descriptions, Sections 4.7 and 4.8, respectively, describe the construction and use of time-slices, including shortcomings, and an examination of statistical relationships within the hierarchical framework.

Table 4.1 List of all indices, ecological component and indicator use; sub-indices are algorithmically combined into higher-order indices.

Attribute	Ecological Element	Description, Use of Indicator
Soil Stability Index (SSI)	Functional	Indicator of soil resistance to erosion, & ability to reform after disturbance.
Water Infiltration Index (WII)	Functional	Indicator of rainfall partitioning into soil-water or runoff.
Nutrient Cycling Index (NCI)	Functional	Indicator of soil organic matter cycling.
Soil Surface Condition (SSC)	Functional	**Sum of SSI, WII & NCI; measure of soil surface health.**
Interpatch Fetch Factor (IFF)	Functional	Prevalence indicator of landscape 'shedding zones'.
Perennial Plant Density (PPD)	Functional	Measure of perennial plant abundance; surrogate indicator of vegetative cover.
Landscape Function Factor (LFF)	Functional	**Sum of SSC, IFF & PPD; measure of landscape functional health.**
Perennial Species Richness (PSR)	Compositional	Measure of perennial species richness.
Response Group Ratio (RGR)	Compositional	Indicator of perennial plant assemblage response to environmental change or disturbance.
Vegetation Composition Factor (VCF)	Compositional	**Sum of PSR & RGR; measure of perennial plant assemblage.**
Berry-bird Plant Ratio (BPR)	Structure	Prevalence indicator of 'berry-bearing' plants and bush clumps.
Plant Size Density (PSD)	Structural	Density of mature (≥ median height) plants; surrogate indicator of plant assemblage viability.
Vegetation Structure Factor (VSF)	Structural	**Sum of BPR and PSD**
Shrubland Range Condition (SRC) Index	Combined functional, compositional & structural elements of ecological health	**Sum of LFF, VCF & VSF; overall measure of ecological health.**

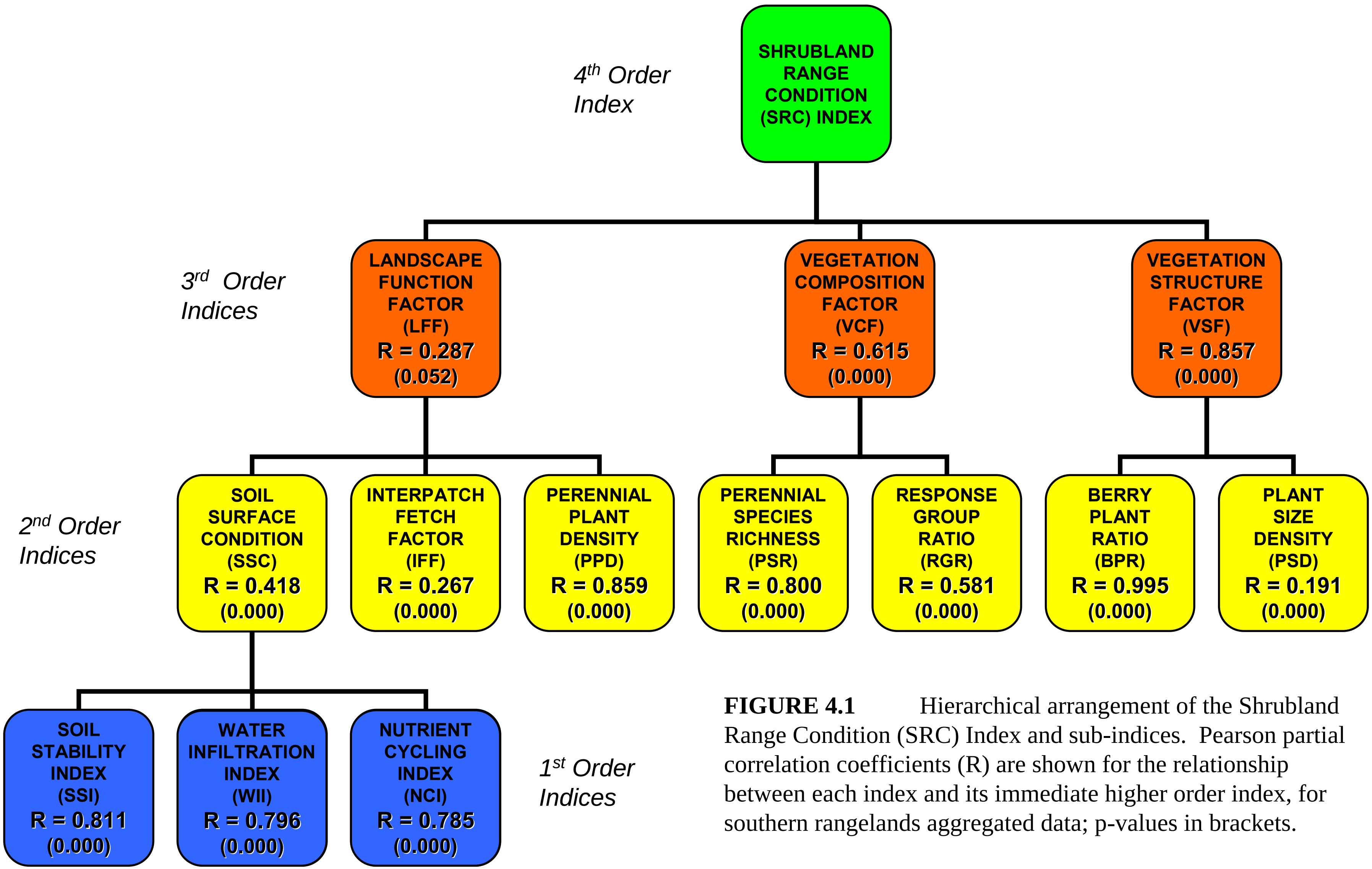


FIGURE 4.1 Hierarchical arrangement of the Shrubland Range Condition (SRC) Index and sub-indices. Pearson partial correlation coefficients (R) are shown for the relationship between each index and its immediate higher order index, for southern rangelands aggregated data; p-values in brackets.

4.3 Soil Surface Condition

The Soil Surface Condition (SSC) index is based on the work by David Tongway as part of his studies on landscape function. This work, which commenced in the late 1980s (Tongway 1990) is concerned with soil-plant interactions, particularly the capture and cycling of water and nutrients, and soil surface stability. Soil surface condition assessment is part of a broader landscape function assessment framework termed by Ludwig & Tongway (Ludwig *et al.* 1997) as Landscape Function Analysis. The analysis is based on the T-T-R-P concept described in Chapter 2. Tongway has developed his findings into a soil health monitoring procedure and is part of the WARMS standard data collection protocol. The following description is from the field manual prepared by Tongway (Tongway 1994) and later updates.

Data is collected along a transect at a WARMS site. Eleven indicators are estimated, then allocated in different combinations to calculate three indices:

- Soil stability (SSI),
- Water Infiltration (WII) and
- Nutrient Cycling (NCI).

Figure 4.2 (over page) shows the allocation of indicators to the three indices.

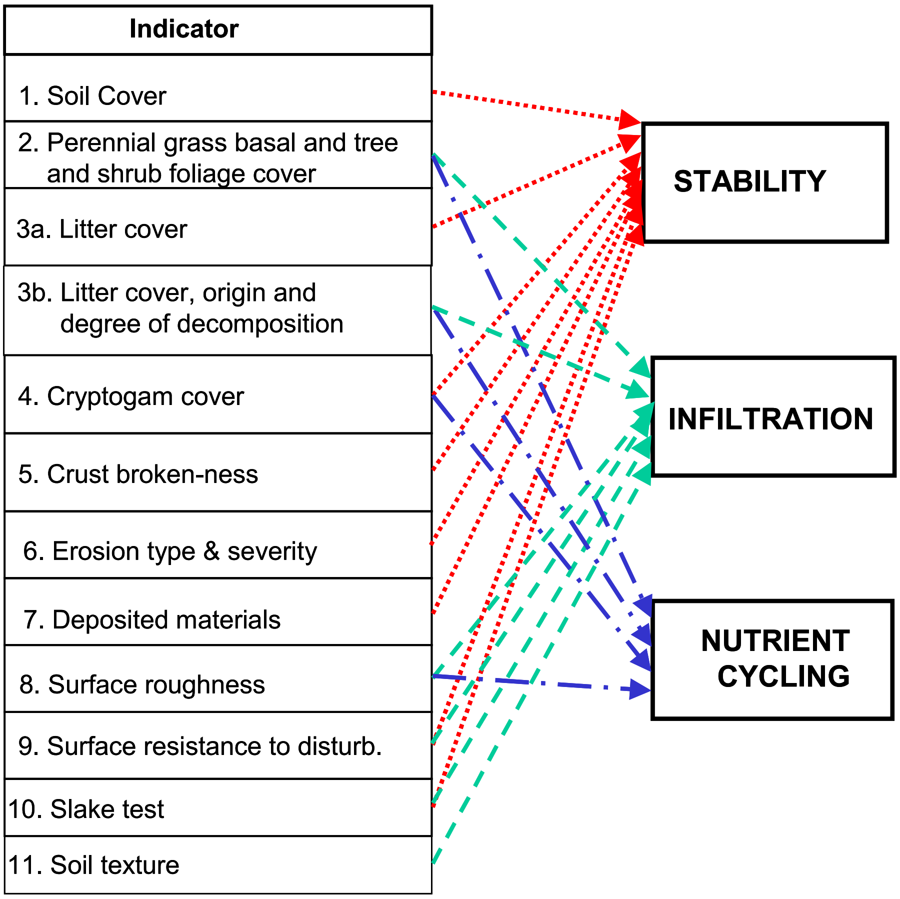


Figure 4.2 Allocation of soil surface indicators to the three indices of Stability, Infiltration and Nutrient Cycling.

Tongway (1994) defines the indices as follows:

(a) Soil stability is the ability of the soil to withstand erosive forces, and to reform after disturbance.

(b) Infiltration/runoff pertain to how the soil partitions rainfall into soil moisture (water available for plants) and runoff water; runoff water is lost from the local system, or may also transport materials (soil, nutrients and seed) away.

(c) Nutrient cycling relates to how efficiently organic matter is recycled into the soil.

For further information on field procedures, and the calculation of indices, the reader is referred to Tongway (1994) and subsequent updates.

4.4 Landscape Function Factor

4.4.1 Introduction

The Landscape Function Factor (LFF) comprises three sub-indices, namely the Soil Surface Condition (SSC) index described above, the Interpatch Fetch Factor (IFF) and Perennial Plant Density (PPD) described below.

4.4.2 Interpatch Fetch Factor (IFF)

Vegetation patches accumulate water, topsoil and organic material. Landscapes or patch-mosaics in healthy functional condition capture and return a higher proportion of these resources to the soil compared to dysfunctional landscapes. In addition to vegetation, capture is also facilitated by fallen tree and shrub woody matter (limbs and stems).

As landscapes degrade through accelerated erosion, patches 'break down' and become dispersed. The resource-shedding zone between patches, called the inter-patch, is characterised by the relatively free unimpeded movement of resources, either downslope when water is the active agent, or downwind when aeolian processes are active. As a result, inter-patch zones become larger as degradation proceeds and this is the basis for the Interpatch Fetch Factor. Fetch is the distance between patches.

The mechanisms of patch-scale resource capture are comprehensively described by Tongway (1994) and Ludwig *et al.* (1997).

The Metric

Expressed as a formula, the Interpatch Fetch Factor (IFF) index is:

IFF = 1 / (Average Fetch + Fetch Range)

Where average fetch is the cumulative length of interpatch zone along the transect (standard 100m distance) divided by the number of interpatch zones and fetch range is the difference between the longest and shortest interpatch zones.

The average fetch and fetch range both increase numerically as patches degrade, allowing previously disconnected interpatch zones to merge into larger shedding zones. However, the IFF is expressed as a reciprocal, so that, numerically, the index increases as landscape resource capture improves.

4.4.3 Perennial Plant Density

This simple index is complementary to the Interpatch Fetch Factor (IFF). The functional role of plants is emphasised here by the inclusion of density in the overall index of landscape functional integrity, namely the Landscape Function Factor (LFF), although it could have been included in the structural integrity index (VSF).

Vegetation, particularly the perennial component, has an important functional role in capturing resources for both itself (self-sustainability) and providing suitable habitat, food and shelter for fauna (Tongway 1994).

As plant density increases (along with diversity), the greater the ability of the landscape as a whole and the vegetation-mosaics and patches to capture scarce and limiting resources. Different parts of the arid landscape have inherently different plant densities; however, a change in density reflects a disturbance of some kind.

Disturbances include storm and flood, fire and herbivory. A change in plant density causes a change in functional ability to capture resources (Holm 2000). This is the basis for the inclusion of perennial plant density within the functional component of the overall range condition index (SRC Index).

The Metric

PPD index = Sum (N_1 +N_2 + N_n) / total transect area (ha)

Where N_n is the number of plants of species $_n$.

4.5 Vegetation Composition Factor

4.5.1 Introduction

The vegetation composition Factor (VCF) is comprised of two sub-indices, namely the Perennial Species Richness (PSR) and Response Group Ratio (RGR). Both are used as surrogate indicators of perennial vegetation composition; annual vegetation is specifically not included. Many studies in the arid shrublands of Western Australia have demonstrated the dominant role that perennial plants play in maintaining properly functioning ecosystems (Williams, Suijdendorp & Wilcox 1980; Hacker 1984; Watson & Holm 1990).

4.5.2 Perennial Species Richness Index

This index is simply the count of perennial plant species occurring at each WARMS site. It is a measure of absolute species richness within relatively standardised sample areas, consistent exclusion of specific short-living species and sampling effect in an attempt to eliminate arbitrary bias. Differences caused by counts being done at different times of the year are thought to be minimal, since only perennial plants are counted.

The transect area used is the standard RTS (Reduced Transect Size) for this and all other indices. It is not a measure of species diversity, since the relative abundance of each species is not incorporated into the metric.

Species richness varies from area to area and local patterns of increase and decrease are frequently associated with disturbance (Lindenmayer & Burgman 2005). In many cases, species which depend on an undisturbed environment may be reduced or eliminated locally, even though regional species richness may increase through the effect of plant invasions.

Although all taxa are assigned equal status in this index, which is a potential weakness if applied alone and uncritically, its application is in conjunction with the other composition index, the RGR discussed below, and with the other vegetation-related functional and structural indices.

The Metric

Expressed as a formula, the 'Perennial Species Richness' (PSR) index is:

$$\textbf{PSR Index} = \textbf{Count}\ (S_1, S_2, S_3 \ldots\ldots\ldots S_n)$$

Where S_n is the number of different species.

4.5.3 Response Group Ratio (RGR) Index

This index is the ratio of the number of decreaser species to the total number of perennial plant species. It is an indicator of perennial plant assemblage response to environmental change or disturbance. All of the perennial species in the WARMS database have been classified as either ‘decreaser’, ‘increaser’ or ‘intermediate’. Decreaser plants are those plants that are sensitive to grazing pressure in particular, but also to other disturbances. Plants in this class are preferentially selected or favoured by livestock because of their relatively high palatability, and because of this, are a sensitive indicator of grazing pressure. Increaser plants on the other hand, are relatively unpalatable.

In circumstances of sustained grazing pressure, the ‘decreaser’ plants reduce in number and the ‘increaser’ plants increase in number. Therefore, the proportion of ‘decreaser’ plants is an indicator of livestock grazing pressure. This knowledge is based on the collective experience of many rangeland scientists and practitioners (Mitchell, McCarthy & Hacker 1988; Russell & Fletcher 2003). ‘Intermediate’ class plants do not show a clear population response, neither significantly decreasing nor increasing.

The Metric

Expressed as a formula, the ‘Response Group Ratio’ index is:

RGR = Count (Individual ‘decreaser’ plants) / total perennial plant count

4.6 Vegetation Structure Factor

4.6.1 Introduction

The Vegetation Structure Factor (VSF) is comprised of two sub-indices, namely the Berry Plant Ratio (BPR) discussed in Section 4.6.3, and Plant Size Density (PSD) discussed below. Both are used in this study as surrogate indicators of vegetation structure since no direct metric or attribute is recorded by WARMS.

In the arid shrublands of Western Australia, the perennial shrubs and trees constitute the dominant and most conspicuous plant growth-forms. A number of authors (Williams, Suijdendorp & Wilcox 1980; Hacker 1984; Watson & Holm 1990) have stressed the very important role that perennial plants play in the long term maintenance of landscape function and viability, that is, good ecological health. Through the maintenance of adequate vegetative cover and growth vigour, the landscape maintains mechanisms to efficiently capture and store water and nutrients within the local environment. Comprehensive explanation of arid landscape patterns and processes is provided by numerous authors, (for example Ludwig *et al.* 1997; Holm *et al.* 2002; Tongway & Hindley 2003; Lechmere-Oertel, Cowling & Kerley 2005) and is discussed further in relation to other ecological health attributes and indicators used in this study.

4.6.2 Plant Size Density Index

Whilst the long term functional or ecological health of shrubland ecosystems is dependent on the presence of healthy perennial plants (Williams, Suijdendorp & Wilcox 1980; Watson & Holm 1990), the question remains as to what is or are, the most appropriate measures or metrics of perennial plant community viability, as just one of several aspects of rangeland health. This is not a simple matter. Aspects of plant population and community dynamics together with some analysis methods are discussed below, along with an explanation of the metric used in this study.

A plant community, assemblage or association can be described as populations of species occupying a particular area or habitat, and a population as a group of plants of the same species, occupying a particular space at a particular time (Krebs 1994). There are complex abiotic (e.g. water balance relations, nutrient uptake) and biotic (e.g. disease, herbivory) processes that drive plant population growth, resulting in recognisable characteristics of populations such as spatial distribution and density. The primary population parameters that regulate plant density are recruitment and mortality. It is on these two parameters and related vital rates, that population dynamics analyses are focussed.

Population analysis methods

Population growth is stochastic not deterministic, thus for a particular species, population growth trend is the net outcome of many individual probabilities. Each plant follows a Markovian growth curve with the probability of death and offspring number and size, being dependent on the individuals' current size, age, status or stage (Holm, Curry & Wallace 1984; Silvertown & Lovett-Doust 1993; Krebs 1994; Easterling, Ellner & Dixon 2000). Matrix population models (also called population projection matrices), including sensitivity and elasticity (perturbation) analyses, are powerful mathematical techniques for the investigation of population dynamics and life-history strategies (see Caswell, Takada & Hunter 2004 for a comprehensive treatment of population modelling). The models are usually constructed using average values of the vital rates (fecundity and survival or age/stage transitions) for each size, age or stage class; population growth rate (λ) is then calculated from which assessments or, more correctly, inferences of population viability can be made.

In the present study, there are two considerable difficulties in applying this approach to establishing population and community viabilities using the WARMS data. The first difficulty concerns the requirement in traditional matrix analysis, that each population needs to be subdivided into discrete age or stage classes. Unfortunately, suitable data for subdivision into natural classes is not routinely collected as part of the WARMS protocol. Of the data collected, only plant size (height and maximum canopy diameter) could be subdivided, but since this measure is a continuous variable with no natural breaks or inflection points [confirmed by the generation and examination of cumulative frequency curves for many species in the WARMS database by this author], any subdivision creates artificial classes with little if any biological meaning.

There have been attempts to circumvent or minimise this difficulty. For example, Easterling, Ellner & Dixon (2000) proposed the use of an ‘integral projection model’ which eliminates the need for subdivision into discrete classes by utilising continuous smooth curves, rather than traditional step functions, for the calculation of size distributions and reproductive values as a function of individual size. This technique is certainly applicable to repeat census data such as the WARMS plant size data but its application in this extensive regional study is limited by the huge computational load. For each of the 450 species in the WARMS database, the size-dependent growth and survival probability densities would first need to be computed for incorporation in the integral projection model and then the model run for each of the species occurring at each of the 980 WARMS monitoring sites, incorporating the data from each census. This compounds to over 30,000 separate first-pass computations of the model.

A second though less sophisticated mathematical treatment involves a numerical algorithm which minimises the distribution and sampling errors associated with assigning individuals to stage classes in a continuous variable. The Vandermeer-Moloney algorithm (cited in Rosenberg *et al.* 2005) could be used with the continuously variable WARMS plant size data, but for this present study the technique also suffers from the same difficulty as the integral projection technique, that is, a huge computational load. Furthermore, the generation of mathematically optimal but biologically arbitrary class stages is an undesirable approach in ecological studies, albeit necessary in some circumstances.

For the reasons given therefore, neither of the above population projection techniques has been used in this study.

The second major difficulty in assessing plant community viability concerns the underlying concept or nature of what constitutes a plant community and how it should be treated in this study. Typically, four characteristics of plant communities are measured and studied:

- Species richness or diversity,
- Growth form and structure; different growth forms determine the structure or vertical 'layering' of the community,
- Dominance; numerically or physically dominant species may exert a major influence on the community, and,
- Relative abundance of constituent species.

Although the above characteristics may be measured and studied, the question still remains as to what is a plant community? Is a community simply a human construct, a concept to help us 'understand' plant dynamics, or is it a natural unit? Krebs (1994 p.449) in his discussion of this issue, recognises the possibility of three end-member types of functional relationship between species, specifically:

- No interaction between species (independent),
- Obligate association of species (dependent), and
- Obligate exclusion (disassociation) of species.

These end member relationships can be thought of as forming a continuum in ternary space and thus a point plotted in this space reflects the degree to which the density of one species is determined by interactions or functional linkages with other species. Clearly, there are natural obligate associations, for example, between parasite and host which have tightly coupled life cycles, but these are relatively few in number. Similarly, clear cases of obligate exclusion are few in number but this relationship is difficult to prove in ecological studies and there may be more cases in existence, particularly in species-rich areas such as the wet tropics.

In the subtropical parts of Western Australia, specifically in the arid shrublands, the extent of dynamic functional interaction between plant species is likely to be low except for specific parasitic or semi-parasitic species such as sandalwood (*Santalum spicatum*), the general passive reliance of plants on the leguminous plants (eg. the Acacias) and other nitrogen-fixing organisms for the provision of soil/bio-available nitrogen, and basic density-dependent competitive effects. If the extent of dynamic interaction is indeed low (and nobody really knows the answer), then it may be prudent to disuse the terms “community” and “association” both of which imply some degree of internal collaboration or functional linkage, in preference for the term “assemblage” which carries less implied emphasis on dynamic functional interactions between species. However, the above consideration of functional dependence is further complicated by facultative ecological associations or the tendency of plants, particularly in arid climates, to occur in clusters, clumps or patches. The characteristic spatial pattern of vegetation was discussed earlier and the development of bush clumps – mixed species of plants forming shrub and tree-base clumps facilitated by berry-consuming birds – is discussed in Section 4.6.3 below. Both of these examples of facultative ecological assemblages may not be functionally dependent in the manner envisaged by Krebs (1994), but are nevertheless, very important strategies of mutual micro-environmental or habitat amelioration.

More important than the nomenclature however, is the high degree of uncertainty of the nature of dynamic relationships between plants in any particular assemblage. For example, given an assemblage at a monitoring site, how do the individual relationships affect the overall viability of that assemblage? With the present poor state of knowledge, it is difficult to know what to ‘do’ with a ‘hand full’ of population growth rates (irrespective of calculation method) in attempting to derive a measure of community or assemblage viability for a particular site. An example of this difficulty is the not uncommon situation where, say, there are 5 species, 4 of which have growth rates > 1 whilst the 5th species has a growth rate much < 1. What is the viability status of this assemblage or site as a whole and can a meaningful 'index of viability' be calculated from the individual population growth rates? The answer is complex, depending in part or wholly on the (unknown) degree of dynamic interaction between species, the relative dominance of each species and the ecological time-frame being considered. Are there key species involved?

Ecological time-frame is important. Various palaeoecological studies, (see citations in Krebs 1994) usually based on pollen analysis, generally show that during major or global climatic shifts to icehouse or hothouse conditions, species within an assemblage act individually according to their own adaptive or functional traits, rather than participating in a common or community-like response to the environmental change. Individual species migrate in time and space along the new environmental gradient, independently of other species and in so doing, become part of other transient (depending on time-frame) assemblages. The climatic changes may be surprisingly rapid, for example, the change to hothouse or icehouse conditions has occurred within decades to a century. Alternatively, during periods of climatic stability such as the Anthropocene (age of humanity), also known as the 'long summer' (Fagan 2004; Flannery 2005) which commenced 8,000 years ago, and in the absence of other perturbations, plant assemblages remained relatively constant.

Although it is not an objective of this study to resolve the issue of species inter-dependence for plants in the arid shrublands of WA, it has been necessary to explore the ecological literature for some measure of community or assemblage viability that could be applied to the WARMS data. No published measure has been found that is sufficiently specific, comprehensive and practical, and which could be incorporated into the suite of rangeland health indicators developed in this study. Therefore, a simple alternative surrogate measure has been developed and is outlined below.

Surrogate plant assemblage viability metric

The continuation of a perennial population depends on a positive balance between recruitment and mortality. Several studies have investigated this relationship for a number of perennial species in the arid shrublands of Australia and the results of this work form the basis of a surrogate plant assemblage viability index developed for use in this present study for WARMS monitoring sites.

For *Atriplex vesicaria* (Bladder saltbush) in chenopod shrublands of eastern South Australia, Hunt (2001) found that the survival of adults makes the greatest contribution to the population growth rate (λ), and that both reproduction and growth of the smaller size classes are factors of lesser importance. This work is supported by earlier work reported by Silvertown and Lovett-Doust (1993) and Tiver and Andrew (1997) for other woody, long-lived perennial species. This key demographic finding provided the important break through in developing a suitable metric of assemblage viability or stability for this study.

The above finding by Hunt (2001) was one of several outcomes from a broader study of the spatial pattern of vegetation changes in response to grazing by sheep. For *A. vesicaria*, a shrub of moderate to high palatability (Russell & Fletcher 2003), Hunt found a characteristic spatial pattern to the determinants of population growth rate within the grazing piosphere. Relatively close to the water point where grazing pressure is highest, the mortality of adult plants had the greater effect on population growth rate whereas at greater distances, recruitment losses had the greater effect. As Hunt explains in more detail, the piosphere expands through two sequential and outwardly expanding impact stages. Initially, grazing causes a reduction in the recruitment of new plants, then, with sustained grazing, increased mortality of established plants follows. This process establishes a distinctive trend of increasing population growth rate with increasing distance from water. Further support on adult plant mortality is provided by Leigh and Mulham (1971, cited in Hunt 2001) who have shown that complete defoliation of adult *A. vesicaria* leads to their death.

In constructing his size-structured matrix population model, Hunt (2001) used four size classes, namely, seedling, juvenile, sub-adult and adult, with the adult class comprising woody plants > 100cm tall. Reproductive values were based on the total number of adults. In contrast, Tiver and Andrew (1997) used nine natural life-stage classes in their study of herbivory effects on the recruitment and regeneration of eighteen perennial shrub and tree species in eastern South Australia. Very importantly, they stated that the presence of juveniles (life-stages I-III), although clearly an indication of recent favourable recruitment conditions, cannot be used as an indication or predictor of long-term regeneration and population viability, because their small size means they are highly susceptible to complete loss through herbivory or desiccation. Instead, Tiver and Andrew (1997) used the ratio of the number of young mature plants (stage IV) to the number of all non-juvenile plants (stages V-IX). Whilst the ecological reasoning for this ratio is sound, its use in the present study, unfortunately, is not possible because of the lack of natural stage classes in the WARMS data, as previously outlined.

The metric

Based on the findings outlined above, that is, that the survival of adults makes the greatest contribution to the population growth rate (λ), an inference of population or assemblage viability is based on the change, between censuses, of the "Plant Size Density" index. The index is simply the sum of plant counts of each species occurring at a particular monitoring site (an assemblage) that equal or exceed its species-specific median height, normalised to a density per hectare value. Short-lived perennial plants are excluded from the index. Expressed as a formula, the "Plant Size Density" (PSD) index is:

PSD index = S (N1 + N2 + …Nn) / Total transect area (ha)

Where Nn is the number of plants of species n ≥ median height (species-specific).

Median height has been selected as the size threshold because it is easily calculated and captures a defined proportion of the population which does not include recruits and small (size) dormant stages. Each species-specific median was calculated using all size records pertaining to that species held in the WARMS database. No account was taken of possible regional size variations. Of the WARMS plant size data, that is, height and maximum canopy extent, either could have been incorporated in the index. Watson (1997) has shown that there is a very strong positive correlation between height and width.

Strengths and Shortcomings

Because the adult plants of many long-lived perennial species are tolerant of a range of environmental conditions, a recognised characteristic of this plant assemblage viability index is that it is not an indicator of light or early (though perhaps increasing) perturbation, particularly the impact of grazing (such as the early suppression of recruitment), and hence is an insensitive indicator of short term changes in population growth rates. For some applications, this characteristic is a weakness whilst in other applications, such as this study, it is a strength. Its strength lies in the fact that recruits are not incorporated in the metric, so that the effect of seasonal recruitment flushes are attenuated. Recruitment flushes occur in response to favourable conditions but, more importantly, survival to adulthood depends on a sequence of favourable follow-up seasons. Given the stochastic nature of the arid zone climate, the continued survival of (reproductive) adult plants is a better indication of long term population viability. In other words, the adult plants have a strong, multi-seasonal stabilising influence on population dynamics.

For the reasons given above, other population dynamics indices which incorporate recruits such as Recruitment rate, Survivorship, Population Growth Rate and

Turnover Rate have not been utilised as indicators of population and assemblage viability or stability in this study.

An example of a weakness of this metric is its insensitivity to the situation where seedlings of one species are being suppressed or removed by herbivory whilst the seedlings of a less palatable competitor are able to increasingly occupy vacant habitats or landscape niches with no net change in total adult numbers (Tiver & Andrew 1997). However, this change in species composition is detected by other metrics such as the Response Group Ratio (RGR) (see section 4.5.3).

4.6.3 Berry Plant Index

Background

A wide variety of birds use the rangelands. These include resident birds with distinct home ranges, nomadic birds which track rainfall- and fire-induced food pulses over large distances, and migrants moving from area to area on a regular basis. Amongst these birds are raptors (carnivores), insectivores, granivores, nectarivores and frugivores; these groups are known as foraging guilds. Fleshy-fruited or berry-bearing plants (or simply berry plants), produce fleshy, usually brightly coloured fruits or arils that are consumed by frugivorous birds and other animals.

The principal assertion on which the development and inclusion of an index related to the frugivore foraging guild, the 'Berry Plant' Ratio (BPR), within a hierarchical suite of indices of landscape functional health, is that for Australian rangelands, vegetation structure has a primary relationship with avifaunal assemblages. Although the relative importance of each vegetation stratum varies for each bird species, foraging guild and geographic region, there is an obvious ecosystem response loop (feedback) which must be effectively operating in order to maintain ecosystem health. For there to be a variety of bird foraging guilds present in any particular area, there must be adequately developed vegetation and habitat complexity. A variety of ecosystem processes maintain the complexity and amongst the essential processes is the role played by birds themselves, particularly the nectarivorous and frugivorous guilds. It is these two guilds principally, which are directly involved in plant reproduction, through cross-pollination and seed dispersal respectively, thereby helping to maintain vegetation complexity. Although the latter aspect is explored in more detail in the section on *Seed Dispersal* below, it is important to recognise that (a) berry plants indicate the presence of frugivore birds, and (b) birds, principally the nectarivorous and frugivorous guilds, help structure vegetation assemblages. The Berry Plant Ratio (BPR), described below, is driven by the presence of berry-bearing or fleshy-fruited plants and thus provides a direct inference of vegetation structural complexity, and an indirect guide to the presence or prevalence of frugivorous birds.

Tassicker *et al.* (2006) found in their landscape-scale study of bird assemblages in tropical savanna ironbark (*Eucalyptus whiteii)* woodland in the Desert Uplands Bioregion of central Queensland, that bird species richness and total frequency are higher in areas of intact vegetation compared to more open areas of mechanically cleared or thinned vegetation. In regard to the eight foraging guilds considered in their study (aerial insectivore, foliage insectivore, ground insectivore, foliage insectivore-nectarivore, nectarivore, granivore, frugivore and raptor) the frugivore guild is most frequent in the densest vegetation cover (45 – 60% cover), the granivore guild in the open areas and the other guilds in areas of intermediate cover density. Whilst this finding should not be transposed directly to the shrublands of Western Australia, it does indicate the likely importance of vegetation structural complexity as an aspect of ecological health; this is discussed below.

Importantly, Tassicker *et al.* (2006) found from their modelling of environmental gradients (habitat variables) that for all but two foraging guilds, responses to both reduced ground vegetation cover and increased grazing intensity were *negative* for both bird frequency and richness. The two guilds which did not show a negative response were raptors and insectivores. Further, in regard to intra-guild heterogeneity, there was no guild within which all members had an equally strong association with the same habitat variable. This is an important point. It indicates the importance of fine-scale habitat partitioning into various foraging niches such as that used for predation, shelter, food sources and nesting materials, and from which one may reasonably infer that structural and compositional changes in vegetation could cause changes in avifauna assemblage composition. Intact vegetation is preferred by many bird species (Tassicker *et al.* 2006) and perhaps by most, with the clear implication that habitat simplification reduces bird species richness. There are, however, several species which are disturbance tolerant or adapted to open areas.

This consideration leads to the widely acknowledged finding from many studies that avifauna assemblages can be strongly affected by livestock grazing (Woinarski & Ash 2002; James 2003; Martin *et al.* 2005) principally through alteration of vegetation structure and composition, and whilst Tassicker *et al.* (2006) have demonstrated, specifically for the savanna ironbark woodlands, that vegetation structure is a key determinant of avifaunal species richness, it is likely that a similar relationship would apply in the shrublands of Western Australia given the even greater vegetation structural and compositional diversity here. This relationship is supported by a localised study in the Goldfields region of the southern rangelands (Daly 2004).

Thus, in a nutshell, this author strongly agrees with the statement by Tassicker *et al.* (2006, p.149) that "…there is no single level of vegetation structure which is best for all [bird] species. Landscape-scale variation in vegetation structure, wherein the habitat requirements of all species are present, is necessary for richness to be maximised." This aspect has also been reviewed and is supported by Kollmann who found that "bird-mediated seed rain of fleshy-fruited species exhibits a high spatial variability which is strongly dependent on vegetation structures" (Kollmann 2000, p.35).

Seed Dispersal

Seeds are dispersed by a variety of mechanisms and agents including gravity, animal-ingestion and -attachment, and wind- and water-borne processes (Silvertown & Lovett-Doust 1993). From an extensive review of literature, Hamrick and Loveless (1986, cited in Silvertown & Lovett-Doust 1993, p.39) found that most wind-dispersed seeds do not travel very far (< 10m) from their maternal parent, whereas animal-dispersed seeds are generally carried much further. Moreover, animal-ingested dispersal frequently results in batches of seeds from the same plant or even from the same fruit being deposited (in the animal faecal droppings) in one or two locations. Seeds cached by birds, insects and mammals also have a similar distribution.

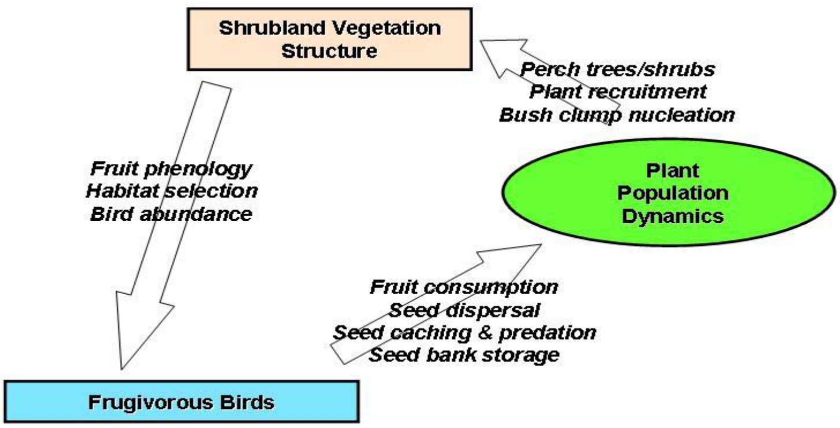
In a study limited to nine species of perennial shrubs in the arid lands of South Australia, Tester *et al.* (1987) found that five shrub species had significantly higher frequencies beneath trees, and of these, three produce berries. The preferential distribution of the three shrub species (the chenopods *Chenopodium gaudichaudianum, Enchylaena tomentosa* and *Rhagodia spinescens)* beneath perch trees was attributed principally to seed dispersal by birds but the authors also suggested that other factors such as edaphic and climatic conditions, and perhaps perch tree branch and foliage architecture (shade quality) may play a role in seedling germination and establishment (recruitment). This aspect is discussed further below.

Seed dispersal is usually a two-stage (primary and secondary) process involving a combination of the agents, mechanisms and processes mentioned above (Silvertown & Lovett-Doust 1993). Importantly, through micro-habitat modification or maintenance, the secondary stage prepares viable seed for later germination when soil moisture and temperature conditions are suitable.

In Johannes Kollmann's comprehensive review of this subject (Kollmann 2000), he emphasises and explains the importance of the mutualistic interaction between frugivorous birds and fleshy-fruited or berry-bearing plants. Interaction processes include fruit removal (consumption), seed rain (deposition) and seed bank dynamics (soil-seed interaction) collectively called dispersal, and seedling germination and establishment, collectively called recruitment; importantly, dispersal and recruitment operate at different spatial scales.

Figure 4.3 illustrates the diffuse, mutualistic relationship between berry-bearing or fleshy-fruited plants and frugivorous birds. According to Kollmann (2000), the mutualistic relationship is diffuse because seed dispersion is usually by several different bird species, rather than by a one-to-one coevolved relationship.

Figure 4.3 Synthesis of the diffuse mutualistic relationship between berry (fleshy-fruited) plants and frugivorous birds in WA shrublands (modified after Kollmann 2000).



Kollmann (2000) argues that bird dispersal processes are strongly determined at the habitat scale, that is, at a larger extent than microhabitat or microsite but less than landscape extent, whereas recruitment is mainly determined at the microhabitat scale. Together, the interaction of dispersal and recruitment processes determine the local abundance of adult berry or fleshy-fruited plants. This was also suggested by Tester *et al.* (1987). Thus, in general, bird mediated seed dispersal often has a significant effect on plant population dynamics and succession. More specifically, as Kollmann (2000) further explains, there are a number of spatio-temporal characteristics of seed dispersal and recruitment of importance. These include, for dispersal, the abundance of frugivorous birds, phenological patterns (matching fruit maturation with bird abundance), seed removal (consumption and transport) away from the high-mortality zone beneath parent plants, the presence of perch trees or tall shrubs (dependent on vegetation structure) often called 'recruitment foci', seed predation by rodents, ants etc and lastly, seed bank dynamics (soil-seed interaction).

For plant recruitment, the two factors of importance are seed germination, mainly determined by the availability of microhabitats with suitable irradiation, soil temperature and moisture conditions, and seedling establishment subject to competitive effects, herbivory and pathogens.

All of the above dispersal and recruitment factors are strongly influenced by vegetation structure at scales ranging from the microhabitat to landscape. Finally, Kollmann (2000) concluded from his literature review, that significant patterns in the distribution and abundance of adult berry or fleshy-fruited plants were present at all spatial scales from microhabitat to biome, each scale reflecting the dominant influence of particular dispersal and recruitment processes.

In their study of the potential for alien (non-native) plant species to transform the Kalahari savanna, Milton *et al*. (2007) focussed attention on the role of host or bird-perch trees in the recruitment of fleshy-fruited plants. Whilst particular findings relate specifically to the Kalahari, some observations are applicable to Western Australian arid shrublands. First, Milton *et al.* (2007) reiterate and support the conclusion by Kollmann (2000) that the dispersal of seeds by birds is essential for the structuring of vegetation and the maintenance of tree and shrub populations in many ecosystems. The fundamental driver here, facilitated by frugivorous birds, is propagule pressure. Because frugivorous birds utilise perch trees and direct seeds via their droppings to subcanopy sites, the formation of species-rich shrub or 'bush' clumps is particularly important. This process is known as nucleation. Importantly however, despite the direct relationship between propagule pressure and recruitment frequency, it needs to be borne in mind, as was discussed in an earlier section, that the ability of a plant species to remain viable depends on enough of its seedlings (recruits) reaching reproductive maturity.

Lastly, from the aspect of monitoring, clumping increases the probability that change in plant assemblage could be detected even for plants present at low density in the landscape (Milton *et al.* 2007). Thus, in addition to assemblage changes being detected by the Berry Plant Ratio (described below), changes are also likely to be reflected by two other indices, the Response Group Ratio (RGR) and Perennial Species Richness (PSR), described earlier.

Role of Berry-bird Plant Clumps in the Landscape

In the shrublands of Western Australia, the effect of grazing on avifaunal habitat condition is only beginning to be reported. Tinley (2005) made insightful observations regarding frugivorous bird habitat, based on extensive aerial and ground surveys of the western and central parts of arid Australia. He observed that the major archipelago habitat type (ecotope), recognisable as an extensive vegetative 'dot pattern' across most landscapes, is the berry-bird formed thickets and bush clumps, and contended that this habitat type is a key functional component in ecosystem dynamics.

The bush clumps and thickets consist of a number of small woody shrubs bearing (in season) brightly coloured fleshy fruits (berries), drupes or arillate seeds that are attractive to frugivorous birds and other animals and insects, and these shrubs are propagated beneath the canopy of a 'perch' tree or larger shrub, and around rock outcrops and other perch features (Plates 4.1, 4.2). Tinley (2005) has identified 64 species of berry plants (26 families, 33 genera) of which 44 species occurring in the Western Australian southern rangelands are browsed by managed and unmanaged ungulate livestock (see Appendix); a high proportion (40% or 26 species) are highly preferred by these herbivores. Berry-bearing or fleshy-fruited plants include short-lived, low shrubs such as *Enchylaena tomentosa* (Ruby saltbush) and *Rhagodia spinescens*, longer-lived shrubs such as *Scaevola spinescens* (Currant bush) and *Chenopodium gaudichaudianum* (Scrambling saltbush), and tall shrubs such as *Pittosporum phylliraeoides* (Native willow).

These observations lead to the understanding that bush clumps and thickets are critical habitats involved in landscape patch-interpatch nutrient and water capture processes as discussed earlier (Chapter 2, Section 2.2.6). Specific benefits provided by bush clumps and thickets include:

- Enhanced plant species richness,
- Enhanced landscape and habitat structural complexity,
- Enhanced biomass productivity,
- Enhanced source of seed (seed bank),
- Improved connectivity of habitat patches for birds and small mammals,
- Enhanced drought resistance and resilience.

Plate 4.1 Bush clump of Scrambling saltbush *(Chenopodium gaudichaudianum),* bearing small red berries, beneath the canopy of a yellow-flowering, bird perch-tree *(Acacia tetragonophylla),* Cashmere Downs station, Goldfields region, southern rangelands, WA.

(Geological hammer for scale; photograph by P. Russell, June 2004)

Plate 4.2 Bush clump comprising Ruby saltbush *(Enchylaena tomentosa)* (see insert), Lake-fringe rhagodia *(Rhagodia drummondii)* and others beneath spectacular flowering Kopi poverty bush *(Eremophila miniata),* Jeedamya station, Goldfields region, southern rangelands, WA.

Photograph by P. Russell, September 2007.

Degradation of bush clumps and thickets is a response to accelerated wind and water erosion facilitated by overgrazing, inappropriate fire regimes and infrequent extreme drought conditions (Tinley 2005). Degradation is expressed as the reduction of berry-plant species richness, physical breakdown and loss (attrition) of accreted soil and organic matter and subdivision (de-coalescing) of larger patches (P. Russell, *pers. obs*.). Degradation is the reversal of accretive processes that characterise the formation of bush clumps and thickets. This degradation is part of a class of multi-scale landscape processes such as fragmentation, dissection, attrition, shrinkage and perforation, recognised (and discussed in more detail) by Lindenmayer & Burgman (2005) as having 'cascading fragmentation effects' including altered ecosystem processes, disrupted species interaction and altered intra-specific dynamics.

Support for Tinley's observation on the importance of the relationship between landscape condition and the presence of foraging birds is provided by Martin in her study of the effect on birds of livestock (cattle) grazing in a sub-tropical grassy eucalypt woodland in southeast Queensland (Martin & Possingham 2005). This study found that bird species' foraging height preference was a good predictor of their susceptibility to grazing. Loss of understorey vegetation through grazing caused a decline in numbers of woodland bird species and, at high grazing pressure, caused a major assemblage change from small-bodied woodland birds to large-bodied 'generalist' birds. As Martin explains (Martin & Possingham 2005) two factors are involved here. The first is that livestock grazing is a potent mechanism by which vegetation structure can be altered, including reduction of ground cover and leaf litter, and second, habitat structure is a strong determinant of bird species diversity. This reinforces the view that a strong relationship exists between habitat condition, particularly structural complexity, and bird species richness. In general, habitats with greater structural complexity support more species than more simply structured habitats, because the former provide more resources and opportunities for micro-habitat segregation, a view reinforced by the more recent study of Tassicker *et al.* (2006) discussed earlier.

Although the four Australian studies discussed above were conducted in different biomes, it is likely that the underlying factors and relationships are applicable across disparate landscapes.

Bird Conservation Status in WA Rangelands

The decline in numbers of birds of the rangelands – for example, the Australian bustard *(Otis australis)* (Ziembicki 2003), the Flock bronzewing pigeon *(Phaps histrionica)* and the Mallee fowl *(Leipoa ocellata)* (*pers. comm.* Malleefowl Preservation Group) – is attributed to declining ecological condition of the landscape. Two earlier studies, Reid & Fleming (1992) and Saunders & Curry (1990), reveal contrasting conclusions regarding the conservation status of WA southern rangeland avifauna, however, the difference is possibly due to different geographic focus, as explained below.

Whilst Reid and Fleming (1992) mainly focus on the western part of New South Wales, they conclude that the status of half of Australia's arid zone avifauna has changed since European occupation due to regional-scale threats. Of the several patterns that Reid and Fleming identified from analysis of 29 threatened and declining species, of foremost importance for this study is firstly, that birds which forage at ground and low shrub height have been the most negatively affected and secondly, that birds associated with chenopod shrublands have been considerably more affected than birds associated with mulga shrublands. The principal regional threat identified by Reid and Fleming is change in vegetation assemblages, through the action of introduced herbivores.

In contrast, the study by Saunders and Curry (1990), which focussed on the Murchison River catchment and utilised both historical accounts and observations made during a rangeland survey programme (1985-88), found no evidence for change in status of the majority (138 of 167 species) of birds. Importantly, Saunders & Curry concluded that the present-day status of any species was not changing rapidly, although they also found that three species had disappeared from the catchment by about 1910. However, most surprisingly, Saunders & Curry found no direct link between the loss of understorey shrubs and perennial herbs in the Murchison River catchment mulga shrublands and changes in bird populations. This finding is in contrast to findings of the studies described earlier and particularly the observations and inferences made by Tinley (2005). It also contrasts with the findings of later work by Curry (2003) outlined below. The difference in findings may relate to scale – regional scale conclusions by Saunders and Curry (1990) in contrast to local scale conclusions by Tinley (2005).

In a carbon sequestration-focussed rehabilitation research project in degraded chenopod-wanderrie grass-mulga woodland (alluvial plain) in the northeastern Goldfields of Western Australia, an initial framework has been devised to monitor landscape function and biodiversity using indicators of ecosystem function at different trophic levels (Curry 2003). One of the four indicators, the indicator for higher-level consumers and dispersal agents, is birds. This study has noted that a bird assemblage of about five species, reduced from 28 or 30 in non-degraded woodland, is recovering, with nine re-colonising species now foraging in the rehabilitated area.

The Metric

Given the accumulating evidence of a strong link between ecological health and birds across a number of rangeland landscapes (Kollmann 2000; Curry 2003; Lindenmayer & Burgman 2005; Martin & Possingham 2005; Tinley 2005; Tassicker *et al.* 2006; Milton *et al.* 2007), it was important to include in this study a 'bird related' attribute in the Shrubland Range Condition (SRC) index. The difficulty however, was that the role of each of the foraging guilds, with the exception of the frugivores, was not quantifiable using available WARMS data, and therefore difficult to develop into a multi-guild indicator. As with all indicators in this study, the berry-plant index has been developed within the constraints imposed by the existing WARMS data collection protocol, as previously discussed (Chapter 3, Sections 3.4 and 3.5).

The work of Tinley (2005) on the key role of frugivores in the shrublands was the vital factor in enabling development of a surrogate co-indicator of vegetation structure and complexity related to ecological health. Using the list of arid shrubland berry-bearing or fleshy-fruited plants used by frugivores compiled and provided by Ken Tinley (February 2005) (see Appendix), all perennial plant species listed in the WARMS database were categorised as either ‘berry-bird’ plants or ‘non-berry-bird’ plants. For each monitoring site and for each census (time-slice), the ratio of the number of berry-plants to the total number of plants was calculated.

Expressed as a formula, the Berry-Plant Ratio (BPR) is:

BPR = Berry plant count / Σ (Berry plant count + non-Berry plant count)

Although the BPR is a compositional ratio, that is, the proportion of berry plants in the plant assemblage, it is also a measure of vegetation structural complexity and presence or prevalence indicator of ‘berry-bird’ bush clumps and thickets (ecotope), and is therefore an indirect and relative measure (rather than direct bird census measure) of frugivore guild activity in the landscape. This ecotope metric is both a contributing indicator to the overall index of landscape or ecological processes and a stand-alone index.

It is important to emphasize that it is change through time, rather than absolute values at a particular point in time, which should enable spatially explicit inferences to be made regarding vegetation structural complexity trends and frugivore population flux.

Strengths and Shortcomings

Strengths of this index are that it is simply calculated and, due to the widespread distribution of fleshy-fruited or berry-plants, is applicable across most land systems in the southern rangelands of Western Australia. With further studies, the berry-bird bush clumps and thickets may be shown to play a keystone role in the WA shrublands as is being suggested by Tinley (2005), that is, a similar role played by scattered trees in African savannahs (Tew 2004, cited in Lindenmayer & Fischer 2006; Milton *et al.* 2007).

A particular shortcoming may be the exclusion of the role of other foraging guilds (through lack of data), which collectively may be as important as the frugivores in maintaining healthy ecosystem function. However, as has been argued, the presence of berry-plants helps maintain the structural and compositional complexity of the shrublands through the establishment of associated bush clumps and thickets; no other foraging guild, alone, appears to have such a key role in vegetation clump or patch formation. These patches provide micro-niches suitable for other types of plants including grasses in some areas which, in turn, based on the conclusions of Tassicker *et al.* (2006), help maintain bird species richness in other foraging guilds in addition to the frugivores.

Given the multiplicity of agents or drivers of environmental change, a general shortcoming is that in the absence of site-specific causal data such as grazing pressure, it is difficult to attribute changes in the BPR to specific causes. Like many of the indicators, this index is affected by plant mortality caused by extreme and/or prolonged drought as well as a range of anthropogenically-accelerated processes, particularly erosion and vegetation compositional and structural change facilitated by overgrazing. Interpretation of this index, and the other suite of indices comprising the overall Shrubland Range Condition (SRC) Index, will rely on the collective spatial and temporal patterns of change. For all indices, the interpretation process involves two principal steps:

- Identifying change through time, and
- Inferring causality where possible.

These aspects are addressed in Chapters 5 and 6.

4.7 Time Slices

4.7.1 Introduction

For individual monitoring sites in the southern rangelands, the WARMS field assessment interval is nominally 5 years with actual intervals varying between 4 years 2 months and 5 years 7 months. Although field assessment of geographical groups of sites is usually done for logistical reasons, the field programme is fairly continuous throughout the year which produces a more or less continuous 'stream' of observation dates and data from disparate sites. Figure 4.4 shows the number of WARMS site observations made per day through the years 1984 to 2006.

This temporal pattern of assessment data creates a number of difficulties for regional change-through-time analysis by statistical and Geographical Information System (GIS) methods.

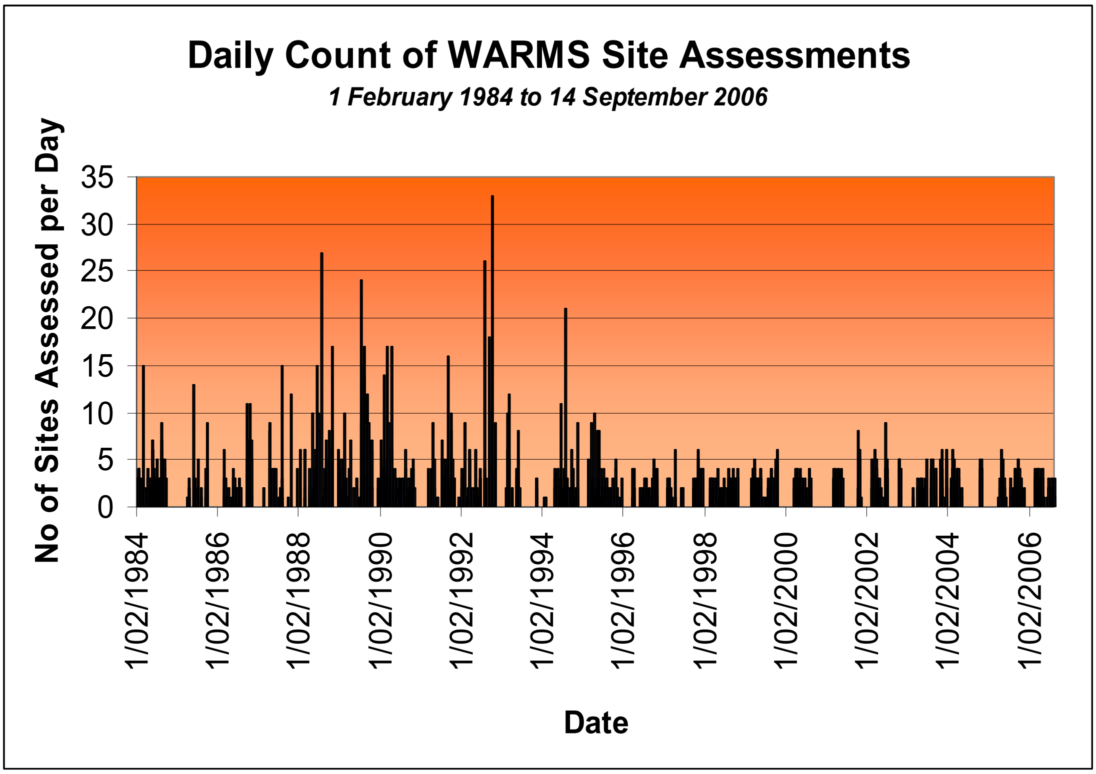


Figure 4.4 Temporal pattern of WARMS site field assessments 1984 – 2006; total number of assessments during period is 4065.

4.7.2 Analysis Difficulties

The two main analysis difficulties caused by the WARMS data collection protocol are:

- The very low number of site assessments available for any particular date (typically 2 to 5 per day) severely limits the usefulness of date-specific regional spatial analysis, and
- The almost continuous spread of observations through time necessitates, for both intra- and inter-regional comparison of sites, the grouping of observations made at different times of a year or in different years, thus confounding complex inter-seasonal effects.

Of course, there is no practical way to field assess all sites in the southern rangelands on the same date so as to provide a date-uniform data set, thus data analysis methods must overcome or at least acknowledge these limitations. The time-slice method was developed to partially overcome this difficulty and is described below.

Time-slice Partitioning

In order to work within the analysis difficulties outlined above for GIS analysis, all WARMS observations have been partitioned into a number of four-year time-slices. The time-slices facilitate map presentation and analysis of change in the Shrubland Range Condition (SRC) Index (and sub-indices) through time and space by providing fixed reference points in time. The time-slices have the following characteristics:

- Each time-slice is four years in duration and includes four summers and four winters,
- The change from one time-slice to the next occurs at 1 October, and
- A four-year time-slice interval avoids the analysis difficulty of having two consecutive sets of observations for a particular site falling within a single time-slice, in those cases where the actual assessment interval is less than the nominal 5-year interval.

Each assessment has also been categorised as either a Winter (W) or Summer (S) observation based on the observation date as follows:

Winter (W): 1 April to 30 September (6 months)
Summer (S): 1 October to 31 March (6 months)

Table 4.2 below lists the calendar year time-slices used to partition the WARMS data for GIS change analysis (Chapter 5).

Table 4.2 Four year time-slices into which WARMS data are partitioned for GIS analysis.

*TIME-SLICE**	*No of SITE ASSESSMENTS*	*No of SITES with SRC Index*
Ts 2002-2006 (Ts 02/06)	646	624
Ts 1998-2002 (Ts 98/02)	825	797
Ts 1994-1998 (Ts 94/98)	646	342
Ts 1990-1994 (Ts 90/94)	584	55
Ts 1986-1990 (Ts 86/90)	902	0
Ts1982-1986 (Ts 82/86)	462	0
Ts 1978-1982 (Ts 78/82) and earlier time-slices	0	0

* The change from one time-slice to the next occurs at 1 October in the common year; total number of assessments is 4065.

In effect, the aggregation of a continuous sequence of observations into a particular time slice or period creates a common observation date, albeit of four years duration. Shorter duration time-slices (for example, two and three years) were considered and tested; however, it was found that there were too few observations in each time-slice to provide adequate spatial coverage, and, most importantly, too few sites common to consecutive time-slices to enable change-through-time analysis. Table 4.3 below lists the number of sites common to time-slice pairs for which the change in SRC Index (ΔSRC Index) was able to be calculated. It is important to realise that the SRC Index can only be calculated for sites where all sub-indices are also available. Thus, the SRC Index is not available for many sites in the earlier time-slices which predate the incorporation of Landscape Function Analysis (LFA) and Soil Surface Condition (SSC) assessments into the WARMS data collection protocol. However, the vegetation related sub-indices, namely Vegetation Structure

Factor (VSF) and Vegetation Composition Factor (VCF) which do not include SSC and LFA in their algorithms, are available for most sites in each of the time-slices and hence their change through time can be mapped.

Table 4.3 Number of sites in each time-slice pair for which change in SRC Index (ΔSRC Index) is available.

TIME-SLICE (Ts)PAIR	*No of SITES with ΔSRC Index*
Ts 98/02 to Ts 02/06	456
Ts 94/98 to Ts 98/02	167
Ts 90/94 to Ts 94/98	55
Earlier Ts pairs	0

Longer duration time-slices were also considered but, apart from introducing the analysis difficulty of multiple observations within a single time-slice, were thought likely to decrease the resolution of change detection. The four-year duration time-slice is close to the five-year field re-assessment interval; a protocol that has been adopted by the Department of Agriculture and Food for both practical and ecological reasons (Hacker 1992) based on many years of experience. A five-year re-assessment interval is also used by the US National Resources Inventory (NRI) for assessment of soil, water and related natural resources on non-federal rural lands (Nusser, Breidt & Fuller 1998). It is expected that four to five years is an adequate period for ecological changes to be expressed at individual monitoring sites and to be detected as change in the SRC Index and sub-indices.

Shortcomings of the Use of Time-slices

The use of time-slices in this study is an attempt to optimise spatial map coverage for change or trend analysis. Clearly, for map depiction of range condition (or any other index or measured attribute), there is a continuum in the number of maps required to track change. At one extreme, a map for each and every observation date would require thousands of maps, each showing only a few sites, and at the other extreme, a single map showing all sites and all observations. In the latter case, most sites would have multiple observations. Neither extreme provides an adequate synthesis or representation of change. Thus, the selection of time-slices spanning four years, close to the nominal field observation interval for sites, is a pragmatic compromise which optimises spatial and temporal resolution for the detection of regional and biogeographical patterns (trends or oscillations) in range condition and other ecological sub-indices.

The most obvious shortcoming is the apparent ‘homogenisation’ of observation dates **within** each four-year time-slice. For example, two adjacent sites with actual observation dates three years apart, say, may be placed into the same time-slice. With a difference of three years, one would expect environmental conditions (e.g. rainfall) to be different. It is possible to compare absolute metrics or indices from each site; however, by having both observation dates in the one time-slice, it is then possible to mistakenly conclude that one site is “doing better than the other” based on the underlying but probably erroneous assumption that environmental conditions were the same for both sites. For sites within time-slices and with closer observation dates, the interpretive pitfalls become less.

In contrast to an apparent homogenisation of observation dates within time-slices, there is an apparent increase in heterogeneity or disparity of observation dates **between** time-slices. For example, the worst case is for two adjacent sites with observation dates only one day apart but straddling a time-slice boundary (1 October), are placed into consecutive time-slices. This causes an apparent difference in observation dates of four years. It is possible to compare metrics or indices from each site; however, by having the two observation dates in different time-slices, it is then possible to mistakenly conclude that one site is “doing better than the other” based on the underlying but probably erroneous assumption that environmental conditions were different. For sites between time-slices and with disparate observation dates, the interpretive pitfalls become less.

Clearly then, particular care needs to be taken when comparing absolute site metrics both within and between time-slices, and in fact, this type of superficial comparison is not recommended by this author. However, the above shortcoming disappears when mapping and interpreting change-through-time values, rather than absolute values at particular times. The apparent shifts in observation dates, given by example above, do not affect the calculation, depiction or interpretation of change since, for every site, the change-through-time of any particular attribute, metric or index is based on the actual field observation dates. Thus, the change calculated for every site is based on its actual sequence of field data, with known observation dates, but presented on maps using **change between time-slices**. This is the key; maps showing change between time-slices (see Chapter 5) do not alter the fundamental data, thus the depiction and interpretation of change for a particular site or between sites, can be undertaken without the interpretative caveats or shortcomings attached to the use of absolute values. The creation of time-slices is simply a convenient tool for synthesising a very large amount of spatial and temporal data into a form that facilitates the detection and mapping of change. The allocation of causal agent(s) to change is, however, another, albeit very difficult, step.

4.8 Statistical relationships within the SRC Index hierarchical framework

4.8.1 Introduction

Non-spatial statistical relationships between the SRC Index and its hierarchically arranged sub-indices (Figure 4.1) were explored using several statistical techniques, namely Pearson product-moment correlation, linear regression, principal component analysis, stepwise regression modelling and Generalised Linear Modelling.

The purpose of the exploratory statistics is two-fold; the first is to determine the relationship and 'strength' of influence of each of the sub-indices on the SRC Index, and second, to test for statistical relationships between the sub-indices themselves. The analysis utilised MINITAB® (Release 14.1) statistical software. Index values were analysed as aggregate data for the entire southern rangelands, that is, the data were not partitioned into subsets such as time-slices, winter and summer observations or into biogeographical regions; however, partitioning was utilised in the spatial-statistical analysis described in the next chapter (Chapter 5).

4.8.2 Test for Distribution Normality

As part of the exploratory statistics, the frequency distributions of log-transformed index values were tested for normality using the Anderson-Darling test (MINITAB release 14.1). This is an empirical cumulative distribution function based test which, for a p-value (observed significance level) lower than the pre-determined level of significance or cutoff (alpha), indicates that the data do not follow a normal distribution. A very low alpha value of 0.005 was used because of the large sample sizes involved.

The graphical output is a plot of normal probability fit-line versus the data being tested, an example of which is shown in Figure 4.5 below.

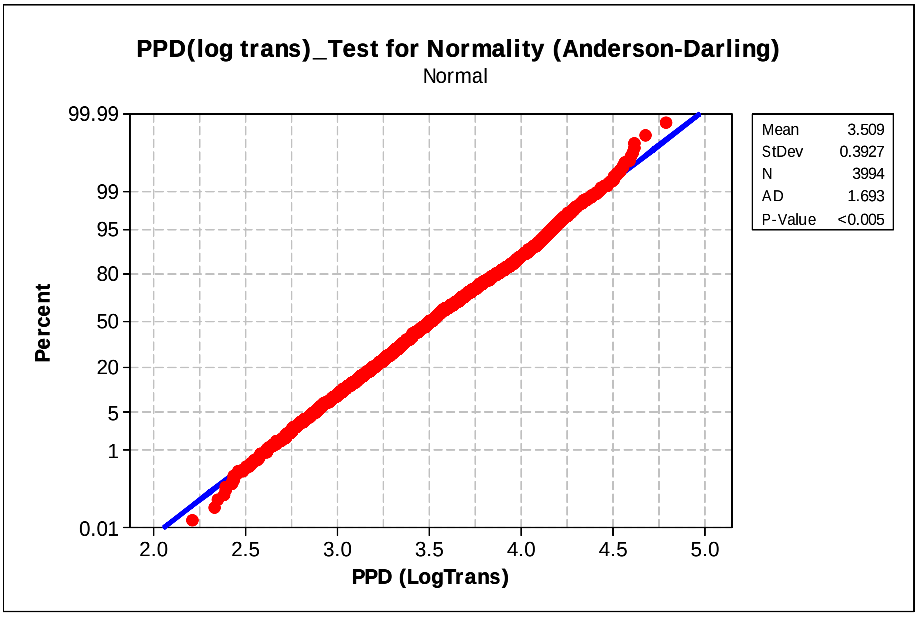


Figure 4.5 Example of the Anderson-Darling test for normality graphical output; the Perennial Plant Density (PPD) distribution (log transformed) (red dots) shows excellent fit to normality (straight blue line).

The goodness-of-fit to normality for the indices (log-transformed data) ranges from excellent to moderate with the exception of the Vegetation Structure Factor (VSF) and Berry Plant Ratio (BPR) which are very poor. Because of the over representation of zero values (berry-bird plants not present at many sites), the BPR distribution is highly negatively skewed with a large departure from the normal fitted line and this has in turn affected the VSF distribution. The other indices however, as expected, show departure tendency from normality only in the distribution tails or extremes, with some indices lighter (lowest values below the fit-line and highest values just above the fit-line) and other indices heavier in the tail (lowest values above the fit-line and highest values below the line). Table 4.4 below lists all the indices in order of decreasing goodness-of-fit to normality.

Table 4.4 Shrubland Range Condition (SRC) Index and sub-indices ranked in decreasing order of goodness-of-fit to normality based on the Anderson-Darling (A-D) test (MINITAB release 14.1); the A-D normality test value is associated with a p-value of < 0.005; N (sample size) is the number of WARMS data records (all years combined).

INDEX	***N (sample size)***	***A-D Normality Test Value***	***Comments***
Perennial Plant Density PPD (log trans)	3994	1.693	Excellent normality fit
Plant Sized-Density PSD (log trans)	3991	1.836	Excellent normality fit
Landscape Function Factor LFF (log trans)	1865	1.886	Excellent normality fit
Nutrient Cycling Index NCI (not trans)	1866	4.777	Very good normality fit
Soil Surface Condition SSC (not trans)	1866	4.856	Very good normality fit
Water Infiltration Index WII (not trans)	1866	5.207	Good normality fit
Soil Stability Index SSI (not trans)	1866	9.788	Good normality fit
Vegetation Composition Factor VCF (log trans)	3961	10.668	Good normality fit
Interpatch Fetch Factor IFF (log trans)	1978	11.229	Good normality fit
Response Group Ratio RGR (log trans)	3961	16.868	Moderate to good normality fit
Soil Surface Condition SSC (log trans)	1866	20.856	Moderate to good normality fit
Plant Species Richness PSR (log trans)	4065	43.747	Moderate normality fit
Shrubland Range Condition (SRC) Index (log trans)	1818	55.421	Moderate normality fit due to adverse effect of VSF
Vegetation Structure Factor VSF (log trans)	3991	651.459	Very poor normality fit due to adverse effect of BPR
Berry Plant Ratio BPR (log trans)	4065	695.951	Very poor normality fit due to excess zero values

The results of the normality testing show that frequency distributions of the aggregated data for each of the indices, except for the Vegetation Structure Factor (VSR) and Berry Plant Ratio (BPR), are acceptably close to normal distributions for sufficiently robust application of parametric statistical methods. Zar (1999) states that although the theory underlying statistical procedures such as analysis of variance (ANOVA) and regression require normal distribution and equal variances, most parametric procedures are sufficiently robust but for the most severe deviations from the theoretical assumptions. Thus, statistical comparison of population parameters of each the indices, with the probable exception of BPR and VSF, can be undertaken if required.

4.8.3 Relationships within the SRC Index hierarchical framework

The above shortcomings with respect to normality do not impede the investigation of the strength of relationships between the indices by correlation analysis and regression. No statistical assumptions need be satisfied in order to calculate a correlation coefficient ($-1 \leq r \leq 1$), a measure of the intensity or strength of statistical association (though not necessarily an ecological association) between two variables (Zar 1999), in this case, the SRC Index and sub-indices. A very similar coefficient, the coefficient of determination (r^2) (occasionally called the correlation index) is a measure of the total variability of one variable accounted for by a second variable, that is, the strength of the relationship. In contrast, a regression coefficient ($-\infty \leq b \leq \infty$) is a measure of the magnitude of change of one variable associated with a unit change in another variable.

A number of statistical techniques were utilised in the exploratory investigation of the nature of relationships between the indices. Techniques included Pearson Correlation, Principal Components Analysis (PCA), simple and multiple linear regression, stepwise regression and General Linear Modelling (GLM); the results of all tests are not individually reported here as there is considerable overlap in the interpretation of the relationships. Rather, interpretation of the relationships within and between the different hierarchical levels is provided by drawing on the results of particular statistical tests as required. Unbalanced analysis was required for most tests. Given the hierarchical interrelationships of the SRC indices, there are two applicable methods of calculating correlation coefficients between indices, namely, simple correlation and partial correlation. It is important to use the correct method, dependent on the actual relationship between the indices under consideration, as inappropriate application results in very different and wrong correlation coefficients.

Simple correlation is only used to test the strength of relationship between two variables where there is no influence from other variables, whereas partial correlation is used where there is interaction from other variables. Partial correlation considers the correlation between pairs of variables while holding the value of the other interacting variable(s) constant (Zar 1999). Thus, for the SRC Index hierarchical framework (see Figure 4.1 for hierarchical structure), simple correlation can be used to test correlations between indices at the same hierarchical level because any pair of indices is value-independent of all others at that level. For example, simple correlation is used to test correlation between, say, Soil Surface Condition (SSC) and Perennial Plant Density (PPD) or Response Group Ratio (RGR), or any of the other 2nd order indices (refer to Figure 4.1). Partial correlation must however, be used when testing correlations between indices at different hierarchical levels. For example, to test correlation between the Landscape Function Factor (LFF), a 3rd order index, and Perennial Plant Density (PPD), a 2nd order index, the values of other indices which contribute to LFF, namely SSC and IFF, must be held constant.

Figure 4.6 (over page) provides a synopsis of the relationships between each of the indices. Examination of the scatter pattern reveals both the nature (positive or negative, or other) and the strength, albeit qualitative (dispersed or tight data scatter), of the relationship. Tables 4.6 and 4.7 below complement Figure 4.6 by summarising results of Pearson correlation analyses of selected indices (simple and partial techniques used where appropriate).

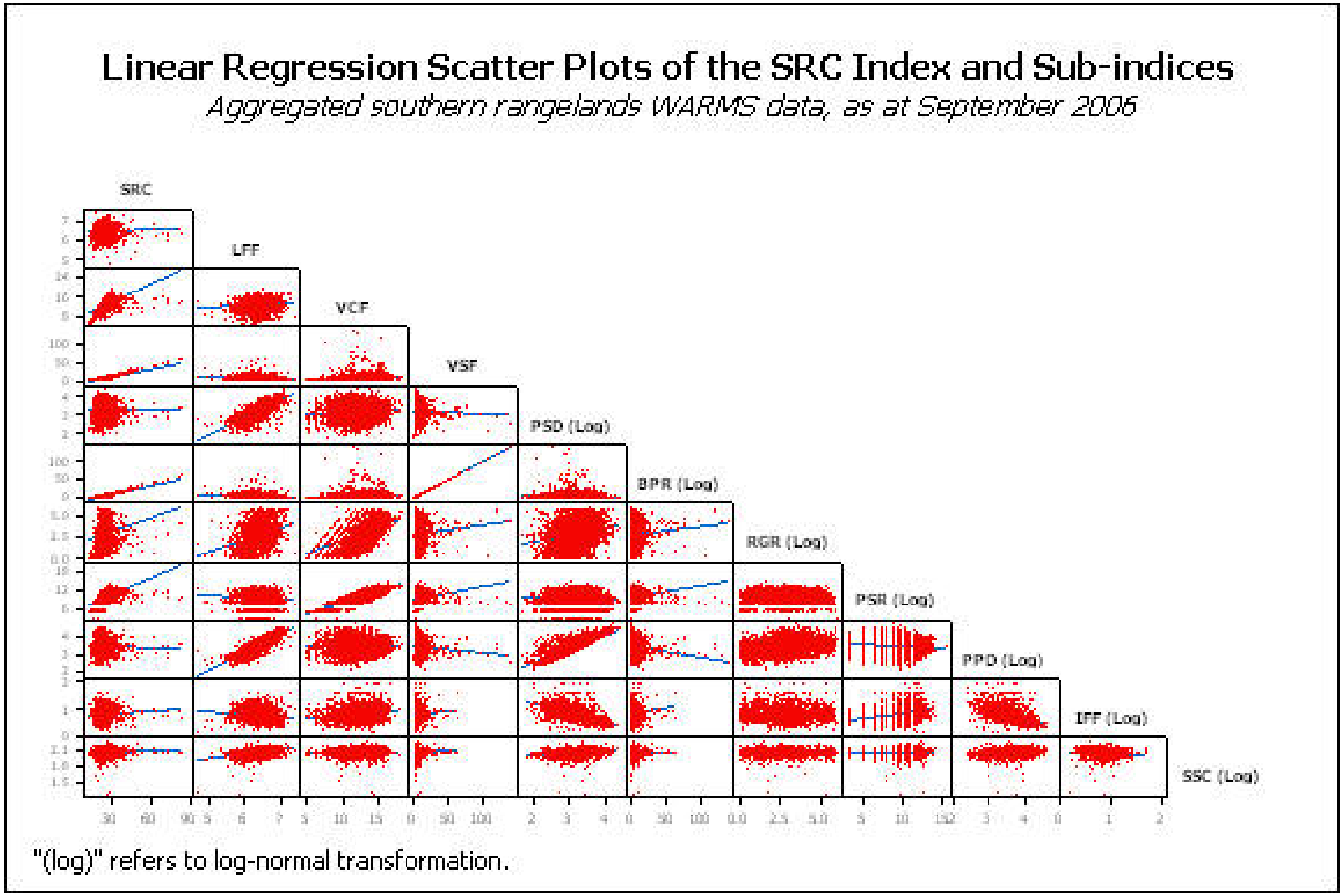


Figure 4.6 **Matrix of linear regression scatter plots of the SRC Index and sub-indices. Index names on the 'diagonal' are column labels for X-axes and row labels for Y-axes. Straight blue line is linear regression 'best-fit' line; regression formulae for selected indices are provided in the text of Section 4.9.3.**

Relationships between the SRC Index and its 3rd order sub-indices

Stepwise regression analysis, utilising both forward selection and backward eliminated methods, gave very similar results, concluding that in order to model SRC Index values, only the three 3rd order indices, namely Landscape Function Factor (LFF), Vegetation Composition Factor (VCF) and Vegetation Structure Factor (VSF), were required. The regression equation is:

SRC Index = 0.00 + 1.00 LFF + 1.00 VCF + 1.00 VSF

[Coefficient of Determination r^2 = 100%; response is SRC Index on 10 predictors; N = 1818; α-to-enter = 0.15, α-to-remove = 0.15]

This of course, is entirely expected and consistent with the hierarchical structure of the indices, indicating that once the 3rd order indices are calculated from their sub-indices, the sub-indices, in effect, become redundant for predicting SRC Index values. However, the regression coefficients shed no light on the strength of the relationships between the indices. Principal Components Analysis (PCA) was used to investigate the relationships further. Results of the PCA of the SRC, LFF, VCF and VSF indices are given in Table 4.5 below.

Table 4.5 Principal Component Eigen Analysis of the SRC Index and immediate sub-indices (LFF, VCF, VSF); 1818 cases used (2247 cases contain missing values).

Eigenvalue	2.134	1.075	0.791	-0.000
Proportion	0.533	0.269	0.198	-0.000
Cumulative	0.533	0.802	1.000	1.000
Variable	**PC_1**	**PC_2**	**PC_3**	**PC_4**
SRC Index	-0.683	-0.031	0.067	0.727
LFF	-0.030	0.857	0.512	-0.040
VCF	-0.416	0.418	-0.748	-0.304
VSF	-0.600	-0.298	0.417	-0.615

Four principal components are identified. The first principal component (PC_1) has a variance (eigenvalue) of 2.134 and accounts for 53.3% of total variance. The principal component scores comprising PC_1 are:

PC_1 = -0.683 SRC Index -0.030 LFF -0.416 VCF -0.600 VSF.

Whilst the interpretation of principal components is subjective, there is a pattern to the coefficients in this analysis. Here PC_1 is unipolar, responding strongly to the SRC Index, the VSF and the VCF (coefficients have same sign and not close to zero) with only very minor effect due to LFF (same sign but close to zero).

The second principal component PC_2 has variance of 1.075 and accounts for 26.9% of total variance. In a similar manner to the interpretation of the first principal component, PC_2 is responding very strongly to LFF, moderately to VCF but weaker and opposite effect to VSF and very minor effect to the SRC Index.

The third principal component PC_3 has variance of 0.791 and accounts for 19.8% of total variance. PC_3 is responding strongly to VCF, and in the opposite direction but less strongly to both LFF and VSF ; the effect of the SRC Index is very minor.

The first three principal components account for 100% of total variance, that is, PC_1 to 3 capture all of the data structure in three underlying dimensions. PC_4 is unimportant and can be ignored.

Examination of regression scatter plots of the SRC Index and its three principal (3rd order) sub-indices (Figure 4.6), show a very weak ($r = 0.287$) positive relationship with the Landscape Function Factor (LFF), a strong ($r = 0.615$) positive relationship with the Vegetation Composition Factor (VCF) and a very strong ($r = 0.857$) positive relationship with the Vegetation Structure Factor (VSF).

The lack of a strong relationship between the SRC Index and the LFF (see Figure 4.6 for more detail) is initially both surprising and disappointing; the simple regression fit is: **SRC Index = 19.55 + 0.79 LFF** ($r^2_{(adj)}$ = 0.1%). Whilst the reason for this dissociation is not obvious, it is possibly related to the nature of ecological relationships such as time-lag effect between changes in soil and vegetation condition and aggregated vegetation types. Lag effects may operate in either direction, that is, change in vegetation condition induces change in soil condition over time, or vice versa; this aspect has not been investigated as part of this study but an additional reason for the low statistical correlation between the SRC Index and LFF is proposed in Chapter 6 based on spatial patterns. Nevertheless, the LFF and its sub-indices are still informative of soil surface condition, change in patch-interpatch fetch ratio and perennial plant density.

The strong positive relationship between the SRC Index and the VCF (Figure 4.6) shows some evidence of a threshold relationship with VCF values tending to plateau at about 16 even for very high SRC Index values. Overall, the relationship is strongly linear; the regression fit is: **SRC Index = 8.39 + 1.32 VCF** ($r^2_{(adj)}$ = 30.5%).

The very strong relationship between the SRC Index and the VSF (Figure 4.6) is very 'tightly' linear over most of the data range except for very low values of both the SRC Index and VSF where a curvilinear relationship is evident. The overall linear regression fit is: **SRC Index = 18.26 + 1.07 VSF** ($r^2_{(adj)}$ = 82.1%).

Table 4.6 Pearson Correlation Coefficients (partial) for the Shrubland Range Condition (SRC) Index and 3rd order sub-indices LFF, VCF and VSF; coefficients > 0.5 are bold (p-values in brackets).

	LFF	*VCF*	*VSF*
SRC Index	0.287 (0.052)	**0.615** (0.000)	**0.857** (0.000)
LFF	--	0.109 (0.000)	-0.066 (0.004)
VCF	--	--	0.155 (0.000)

Perusal of Table 4.6 also shows very weak correlation between the three 3rd order indices. This again, is initially surprising, given that several of the 2nd order indices (which contribute to the 3rd order indices) have medium to strong correlations with each other (see Table 4.7). For example, Plant Size Density (PSD), which is a contributing index to Vegetation Structure Factor (VSF), has a very strong positive correlation (r = 0.846) with Perennial Plant Density (PPD) which contributes to the Landscape Function Factor (LFF). The reason(s) for the weak correlations between LFF, VCF and VSF have not been investigated here but it is surmised that much stronger correlations would be evident within similar landscape or vegetation assemblages, rather than the disparate assemblages considered here for the entire southern rangelands. Partitioning of the Nullarbor chenopod region from the remainder of the shrublands would improve correlation between the various indices.

Relationships between the 3rd order indices and their 2nd order sub-indices

Having considered relationships between the SRC Index and its 3rd order sub-indices, it is now appropriate to consider the relationships between the three 3rd order indices and each of their 2nd order sub-indices. Reference can be made to Figure 4.6, (matrix summary scatter plots) and Figure 4.1 (SRC Indices hierarchical framework diagram). In regard to the Landscape Function Factor (LFF), its contributing 2nd order indices are Soil Surface Condition (SSC), Interpatch Fetch Factor (IFF) and Perennial Plant Density (PPD) and each has a different relationship with LFF. The strongest relationship is with PPD. This shows a very strong positive correlation with a 'tight' linear scatter of data around the regression line; the regression fit is: **LFF = 4.16 + 0.64 PPD** ($r^2_{(adj)}$ = 65.1%). In contrast, much weaker associations with LFF are expressed by SSC (regression fit: **LFF = 2.60 + 1.83 SSC**) ($r^2_{(adj)}$ = 13.6%) and IFF (regression fit: **LFF = 6.54 - 0.17 IFF**) ($r^2_{(adj)}$ = 1.5%), both showing dispersed scatter of data about the regression line. SSC shows a positive correlation whilst IFF shows a slight negative (inverse) correlation.

In regard to the Vegetation Composition Factor (VCF), its contributing 2nd order indices are Perennial Species Richness (PSR) and Response Group Ratio (RGR). Both indices have strong positive correlation with fairly 'tight' linear scatter of data around the regression line; regression fits are: **LFF = 2.91 + 0.99 PSR** ($r^2_{(adj)}$ = 67.8%)and **LFF = 9.59 + 0.97 RGR** ($r^2_{(adj)}$ = 30.3%)

The final 3rd order index, the Vegetation Structure Factor (VSF) has two 2nd order contributing indices, namely the Berry Plant Ratio (BPR) and Plant Sized Density (PSD). These indices show radically differing relationships. The BPR exhibits very strong positive correlation with VSF with an extremely 'tight' scatter of data around the regression line; the regression fit is: **VSF = 3.22 + 0.99 BPR** ($r^2_{(adj)}$ = 99.7%). In diametric contrast, PSD exhibits very weak, slightly negative (inverse) correlation with VSF; the regression fit is: **VSF = 7.59 - 0.46 PSD** ($r^2_{(adj)}$ = 0.0%).

Relationships between the 2nd order indices

Table 4.7 below tabulates the correlation coefficients between all 2nd order indices. Notable is the general paucity of strong correlations with only three index pairs having an r-value greater than 0.5, and of these, two have an inverse relationship. The strongest correlation (r = 0.85) is between Perennial Plant Density (PPD) and

Plant Sized Density (PSD). This relationship is expected. As the total plant population increases (PPD), the proportion of plants above the median height should also increase; however, in the situation where PPD increases but PSD does not, this is indicative of an altered plant assemblage dynamic. An example is a recruitment 'flush'.

The other two moderately strong correlations, between the Interpatch Fetch Factor (IFF) and PPD (r = -0.56) and PSD (r = -0.54), are both inverse relationships. This is contrary to the expectation that as total plant density (and PSD) increases so too does the IFF, reflecting an increase of vegetated patches and corresponding decrease of poorly vegetated interpatch zones. The reason for this apparent contradiction has not been investigated in this study but may be due to data being aggregated for the entire southern rangelands; in both cases, there is a fairly large amount of scatter around the regression lines. Analysis of individual vegetation types may resolve this relationship.

Table 4.7 Pearson Correlation Coefficients (simple) between all 2nd order sub-indices; coefficients > 0.5 are bold (p-values in brackets).

	IFF	***PPD***	***PSR***	***RGR***	***BPR***	***PSD***
SSC	-0.103 (0.000)	0.193 (0.000)	-0.041 (0.078)	0.041 (0.081)	0.022 (0.342)	0.215 (0.000)
IFF	--	**-0.560** (0.000)	0.277 (0.000)	-0.052 (0.023)	0.082 (0.000)	**-0.542** (0.000)
PPD	--	--	-0.117 (0.000)	0.258 (0.000)	-0.130 (0.000)	**0.846** (0.000)
PSR	--	--	--	-0.020 (0.199)	0.147 (0.000)	-0.029 (0.070)
RGR	--	--		--	0.050 (0.002)	0.242 (0.000)
BPR	--	--	--	--	--	-0.082 (0.000)

Several other correlations between the 2^{nd} order indices, although not strong, are of interest. The Interpatch Fetch Factor (IFF) is positively correlated with the Plant Species Richness (PSR) index (r= 0.3), the Response Group Ratio (RGR) is positively correlated with both the Perennial Plant Density (PPD) (r = 0.3) and Plant Size Density (PSD) (r = 0.2) indices, and the Soil Surface Condition (SSC) is positively correlated with both the PPD (r = 0.2) and PSD (r =0.2). Although all of these relationships are weak, and much weaker than expected, it is suspected that the relationships would strengthen for particular vegetation or soil-landscape types.

4.9 Summary

This chapter described the basic indices developed to measure various soil and vegetation attributes, and their incorporation into a hierarchical indexical framework culminating in a single index of ecological integrity. A key aspect has been the use of time-sliced indices, based on field data acquisition date. This work has provided a solid foundation for the investigation of change through time, the results of which are explored in the next chapter.

There is an obvious range of correlations between the SRC Index and each of the sub-indices from very strong to very weak and these have been ranked in decreasing strength in Table 4.8. The reason for poor correlation between the SRC Index and some of the sub-indices is thought to be related to several factors related to the hierarchical index structure, data aggregation of dissimilar landscape and vegetation types and to fundamental ecological relationships or processes.

Table 4.8 Ranked tabulation of Pearson correlation coefficients R > 0.5 for the SRC Index and sub-indices.

INDEX PAIR	***CORRELATION COEFFICIENT***
VSF - BPR	+0.995
LFF - PPD	+ 0.859
SRC Index - VSF	+ 0.857
PPD – PSD	+ 0.846
SSC - SSI	+0.811
VCF - PSR	+0.800
SSC - WII	+0.796
SSC - NCI	+0.785
SRC Index - VCF	+ 0.615
VCF - RGR	+0.581
IFF - PPD	- 0.560
IFF - PSD	- 0.542

Statistical correlation of IFF with PPD and PSD, both vegetation related indices, is moderately strong but negative. The reason for this has not been resolved but is likely to be related to lag effects and/or disparate spatial patterns of variation. This explanation also applies in the cases where there is weak correlation; nevertheless, the indices remain useful for elucidating changes in soil and vegetation condition.

5 Range Condition and Change in the Southern Rangelands

Chapter 5: RANGE CONDITION and CHANGE IN THE SOUTHERN RANGELANDS

This chapter presents evidence of spatial and temporal patterns and changes in the ecological integrity or range condition of the southern rangelands of Western Australia. The work is founded on a hierarchical suite of indices derived from soil and vegetation metrics captured from WARMS transects over the last 16 years. Time-sliced data are used to examine change through time and to postulate causes of change.

5.1 Introduction

Change in soil and vegetation attributes through time, in response to climatic conditions, herbivore grazing, fire and other natural and anthropogenic influences in the rangelands is known as change in range condition. If the change persists in a certain direction, spatially or temporally, it may be recognised as having a trend. When range condition is used in an ecological context, as it is in this research, an improving trend or positive change reflects an increase in soil stability, water and nutrient capture and cycling, and/or an increase in vegetation structural and compositional complexity. This implies an improvement in ecological or ecosystem integrity and contrasts with a declining trend which implies a reduction in integrity, otherwise known as natural resource degradation.

However, the spatial extent to which condition and change of condition observed at point monitoring sites, such as the WARMS sites used in this study, can or should be extrapolated is subject to considerable uncertainty. This issue was discussed in Chapter 3 (Section 3.5). Nevertheless, there are a number of useful inferences and insights that can be gained from examination of the regional and local spatial and temporal patterns in range condition described below.

5.2 Objectives

The objectives, map and analysis requirements are closely tied to the questions to be answered. There are three related types of questions. The first is of the type *“What does range condition look like in the southern rangelands?”* This is a frequently asked leading question and is the most easily answered by maps depicting patterns of range condition (using the SRC Indices developed for this purpose) at particular points in time. This question is usually quickly followed by *“What is the range condition trend doing?”* Again, this is answered by maps showing the change in range condition (Δ SRC Indices) through time for each monitoring site, clusters of sites or across the entire region.

The second type of question is usually along the lines of *“Are there any particular pastoral stations/soils/vegetation assemblages/land systems/catchments or IBRA regions which are associated with markedly declining (or improving) trend in range condition?”* This type of question is much more difficult to answer given that within any particular tenure or biophysical landscape unit, not all monitoring sites will necessarily show the same trend (direction and magnitude) in range condition. Also, as was discussed in Chapter 3, there is a severe intrinsic spatial interpolation limitation associated with point monitoring. This question, although incompletely answered here, could be answered much more fully by further analysis using GIS spatial intersection techniques and the data generated by this study.

The third type of question concerns agents of change. For example *“What is/are the underlying cause(s) of the trends in range condition?”* This is by far the most difficult question to answer for at least two reasons. First, it is likely that observed change is due to multiple agents or drivers (multifactorial), confounded by complex time-lagged feedback loops, with the contribution of individual agents difficult to isolate. Second, there is a severe paucity of WARMS site-specific data on agents of change. The best that can be done is to make inferences from the patterns and relative changes shown by the SRC indices, or to construct numerical temporal-spatial models incorporating plausible agents, based on the patterns of change. For southern rangeland WARMS sites (the subject of this study), the most conspicuous or likely agents of change are climate, particularly seasonal and long term rainfall trends, and livestock grazing pressure. Other agents of change include infrastructure such as roads and tracks, mine openings and associated processing plant, townships and associated human activities. Again, this study has only touched on this aspect, leaving most of the question unanswered.

A suite of maps and spatial analyses required to answer the above questions is outlined below.

To answer questions of the first type (range condition pattern and trend):

- Point-based depiction of the SRC Index and its principal sub-indices (LFF, VCF, VSF) for the most recent time-slice (Ts2003-2006) and each of the preceding time-slices.
- Point-based depiction of the change in the SRC Index (Δ SRC Index) and sub-indices between time-slice pairs.

To answer questions of the second type (spatial associations):

- Spatially interpolated ΔSRC Index and sub-indices (ΔLFF, ΔVCF, and ΔVSF) intersected with selected biophysical landscape units. Individual pastoral stations and some biophysical units contain too few sites for effective interpolation.

To answer questions of the third type (spatial modelling of agents/drivers of change):

- Spatially interpolated or aggregated ∆SRC Index and sub-indices (∆LFF, ∆VCF, and ∆VSF) intersected with seasonal and long term rainfall trends, and livestock grazing pressure. Analysis of variance (ANOVA) to test the strength of associations cannot be done, however, due to the paucity of spatially explicit data on the drivers of change.

5.3 Analysis Pathway (Methods)

5.3.1 Introduction

The data analysis pathway is shown in Figure 5.1. Following conceptual development of the hierarchical SRC Index framework, described in the previous chapter, the two main sequential phases involved in producing range condition and change maps, were:

(i) Calculation of indices, and

(ii) Mapping of indices.

Although calculation of the SRC indices and their relationships to each other are covered in the preceding chapter, some additional comments are provided which lead into and are integrally tied to the second phase, the mapping and interpretation of thematic SRC Index maps.

5.3.2 Calculation of Indices

Calculation of indices involved the writing of a suite of MS Access queries to interrogate the WARMS relational database. For each WARMS site, this process extracted relevant metrics, calculated indices, and combined separate index tables

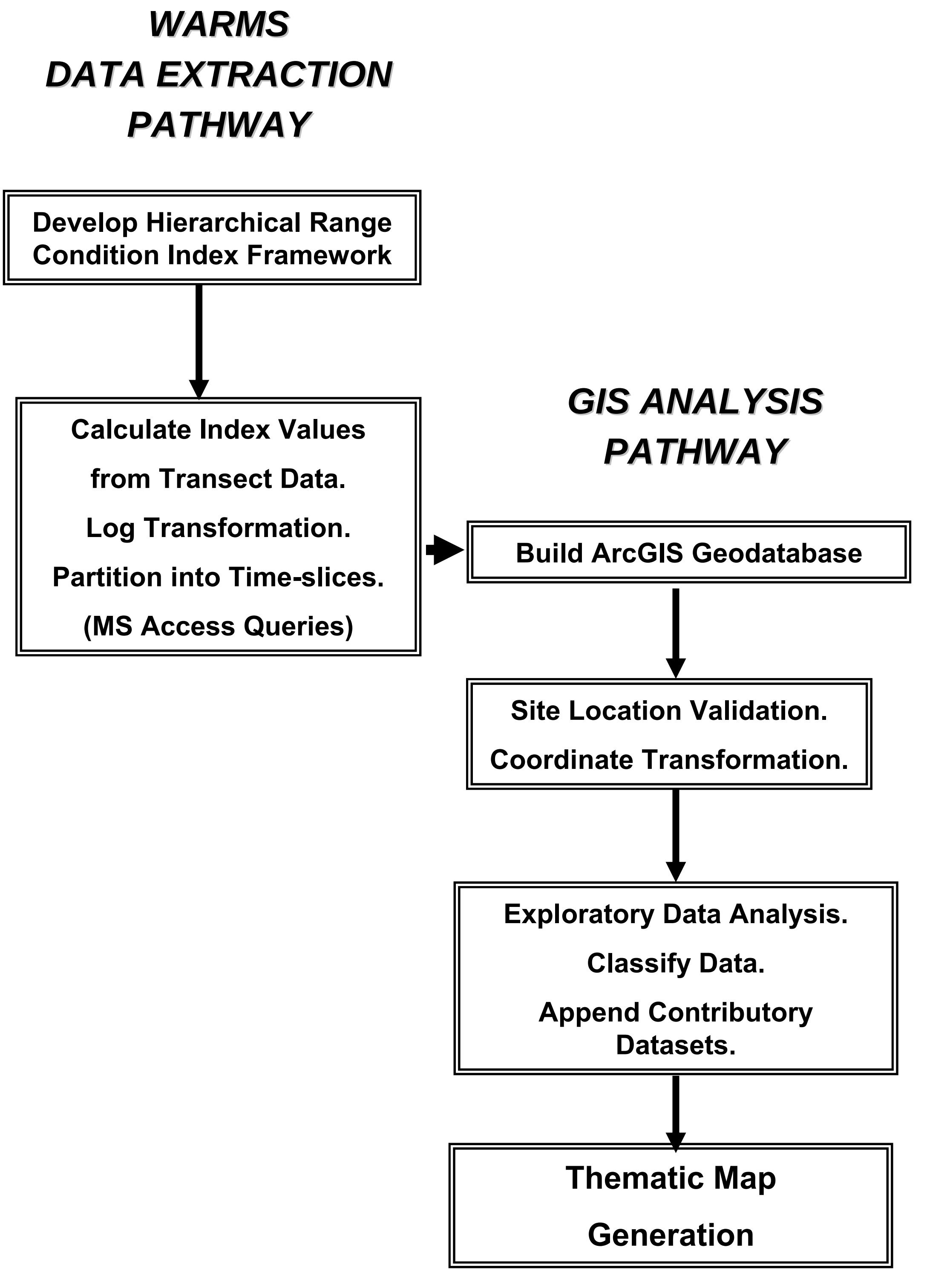


Figure 5.1 WARMS data extraction and GIS analysis pathways.

into a master MS Access table matched with location and other relevant site attributes.

For a number of reasons, this was not a straightforward process. Apart from the necessary computing requirements to handle the very large WARMS relational database, planning and query development took into account data quality (site type, uniformity of measured units, field protocol conformity), the sequence in which indices needed to be calculated (an iterative process, given that higher-order indices could not be calculated until lower-order indices had been calculated), and various conditions and criteria. In addition, indices were allocated to time-slices based on the field capture date of the metrics used to calculate the index (see the previous chapter for a full discussion). Finally, the first and second order indices were logarithmic transformed to generate normal frequency distributions before being algorithmically combined to form higher order indices. The log transformation is fully described in the previous chapter, as are the statistical relationships between indices.

For all SRC indices, the higher the absolute value, greater is the implied ecological integrity or range condition.

Although the hierarchical index framework and time-slice concepts are simple, the practical manipulation of database data into a form suitable for GIS analysis was, in this case, complex and time consuming.

5.3.3 GIS Mapping of Indices

The master MS Access table was used as the principal input for this phase of work, the GIS analysis. The main steps in the GIS analysis pathway (Figure 5.1) consisted of the following:

(i) ArcGIS Geodatabase creation,

(ii) WARMS site location data validation and datum transformation,

(iii) Exploratory data analysis,

(iv) Thematic map generation,

An *ArcGIS geodatabase* was built from the master MS Access table containing all the SRC indices and WARMS site attribute data. This critical step allows data to be mapped and spatio-temporal analysis to be undertaken. The geodatabase contains spatially attributed feature datasets, feature classes and subtypes (used to differentiate groups of features within feature classes) and topology rules that structure how polygons are related to each other and associated attributes.

The next step involved the *validation of site location data*. Validation issues included missing location coordinates, invalid locations (for example, sites located in the Indian Ocean), duplicate locations, coordinate transformation errors and datum errors. Resolution of some site locations required accessing original source maps and data. All location data was transformed to a common geodetic datum, namely, the latest Australian geodetic datum, GDA94 (latitude and longitude), from multiple source data (AGD66, AGD84, AMG84, WGS84 and GDA94). This essential step was then followed by projecting the data from GDA94, a geographic coordinate system, to the MGA94 Zone 51 projected coordinate system to enable distance-based analysis.

Exploratory data analysis (EDA), was undertaken next. This identified regional and sub-regional patterns in the SRC indices, indicating that the data are not random. Further examination of the data by time-slice indicated that variation through time is also not random.

Various ancillary spatial data sets such as geology, soil, landsystem and drainage were appended to the geodatabase by spatial-join. In addition, rainfall maps, georeferenced to MGA94 Zone51, were overlain on the SRC Indices map layers. Examination of spatial associations revealed patterns, including linear features, which suggested contribution to the range condition patterns by some of the ancillary data.

Thematic map generation and interpretation continued on from EDA, involving the examination and interpretation of spatial and temporal patterns shown by the SRC indices. Regional spatial patterns were confirmed by ArcGIS Geostatistical Analyst trend analysis and local patterns were confirmed using Morans-I function (within Geostatistical Analyst). Creation of interpolation surfaces was done using Inverse Distance Weighting (IDW) technique within the ArcGIS Spatial Analyst extension. More information on the reason for using IDW is given in the next section as part of the discussion on data classification. The final step (not illustrated in Figure 5.1) in the pathway is the creation of presentation maps.

5.3.4 Indices Classification

Classification of data for GIS (Geographic Information System) map interpretation and presentation is an important step. Maps which reflect the partitioning of data into classes are called cloropleth maps. An aim in this study is to display the data in meaningful classes that are (a) visually effective, (b) established objectively and (c) consistent between time-slices and across spatial entities. Given that the SRC Index and its sub-indices are continuously varying quantities lacking natural breaks or structure (which, if present, could have been used as logical class breaks), a serial method in which the limits or boundaries (breaks) of each class have a direct, objective mathematical relationship with each other (Burrough 1996), was chosen to be the most suitable classification method.

Examination of the frequency distribution of each of the indices (see Chapter 4 for more information on distributions and hierarchical relationships) shows that most are normally distributed, though with some positive or negative skewness. Using the entire dataset (all observations) for each index, each is divided into five classes, defined as a proportion of the standard deviation (s or σ), dispersed either side of the mean (μ) with class breaks placed at: μ-1.5σ, μ-0.5σ, μ+0.5 σ and μ+1.5 σ. Classes are then assigned colour-coded symbols and short descriptors or labels to facilitate map visualisation. Table 5.1 lists the class intervals and associated descriptors.

Table 5.1 Class definitions used for classifying values of the SRC Index and sub-indices to produce cloropleth maps; μ is mean, σ is standard deviation.

CLASS DESCRIPTOR	*CLASS INTERVAL*	*CLASS LIMITS*
"Very Poor" or "Very Low"	variable	< μ-1.5σ
"Poor" or "Low"	1σ	μ-0.5σ to μ-1.5σ
"Fair" or "Moderate"	1σ	μ-0.5σ to μ+0.5 σ
"Good" or "High"	1σ	μ+0.5 σ to μ+1.5 σ
"Very Good" or "Very High"	variable	> μ+1.5 σ

Each index value is absolute, having been calculated from field measured metrics, but classification of values into classes based on the method described above produces classes relative to the entire index data set. However, a particular index value, classed as, say, "Good", will retain that classification throughout all time-slices, essential to enable consistent comparisons through time and between spatial entities. This method is preferable to an exogenous method where class intervals are based on externally sourced limits or cut-off values that may be relevant to but are not actually derived from the data set itself. Similarly, arbitrary class intervals, chosen without proper consideration of the data and purpose of the analysis and which do not meet the aims mentioned above, are not acceptable.

A weakness of the above classification method is that reference values are not included. This, unfortunately, was unavoidable given the paucity of benchmark sites encompassing the entire spectrum of range condition from which a set of reference SRC Index (and sub-index) values could have been calculated and used to classify the entire dataset. However, this weakness is not crippling since the design and principal objective of WARMS is to monitor change through time and that remains the core focus of this work.

The temporal change maps, showing the change in index values between time-slices, are calculated from the difference in absolute index values at each time-slice and then the resultant value is classified using the entire change data set using the same class definitions listed above. The only difference is in the short descriptor or label given to each class, necessary to reflect that it is change being mapped, rather than status or condition at a particular point in time. Table 5.2 lists the class intervals and associated descriptors for the change maps.

Table 5.2 Class definitions used for classifying values of the ∆SRC Index and sub-indices to produce cloropleth change maps; μ is mean, σ is standard deviation.

CLASS DESCRIPTOR	*CLASS INTERVAL*	*CLASS LIMITS*
“Substantial Negative Change”	variable	< μ-1.5σ
“Moderate Negative Change”	1σ	μ-0.5σ to μ-1.5σ
“Nil or Minor Change”	1σ	μ-0.5σ to μ+0.5 σ
“Moderate Positive Change”	1σ	μ+0.5 σ to μ+1.5 σ
“Substantial Positive Change”	variable	> μ+1.5 σ

The range condition change (∆SRC Index) maps (Figures 5.8, 5.12 and 5.17) are shown as interpolated surfaces. Using ArcGIS Spatial Analyst, these maps were created by an IDW interpolation technique (power value 2) using a 50km and five neighbours search radius (anisotropy factor 1). Output cell size is 5 x 5km. All

∆SRC site and interpolated surface output values were then classified using the definitions given in Table 5.2.

Other interpolation techniques were examined and trialled, but IDW was selected as the most appropriate technique for the requirements of this project. The principal advantage IDW has over other techniques, particularly kriging (all types), is that it is better at maintaining the value of the predicted or interpolated surface very close to the actual site (point) value, even where large differences occur between adjacent sites (Burrough 1996). In other words, the integrity of high-variance data is better maintained.

Use of an interpolation technique recognises that WARMS sites are intended to be representative of a larger area. Given that these areas are, in general, located in more stable parts of the landscape, it is axiomatic that if negative or adverse change is detected at sites, then change is occurring at a greater rate in the more active, geomorphic process-linked zones or alleys. However, these active zones are not specifically monitored. For this reason, it is important to recognise and highlight WARMS sites or more importantly clusters of sites showing change, particularly adverse or negative change. The interpolation technique facilitates this process.

However, also for the reasons given above, it is important to appreciate the converse situation. Where no or minimal change is mapped, change may be occurring in active zones that is not yet being detected at the process-linked WARMS sites.

5.4 Spatial and Temporal Changes in Range Condition

5.4.1 Introduction

The following discussion of range condition in the southern rangelands of Western Australia addresses three aspects. First, the pattern or status of range condition, based on classified values of the Shrubland Range Condition (SRC) Index and its principal sub-indices for each of the four time-slices (Ts) listed below is examined. This aims to answer the first type of question mentioned above *"What does range condition look like in the southern rangelands?"* The answer is provided for each time-slice, in sequence from the earliest (Ts1990-1994) through to the latest time-slice (Ts2002-2006):

- Ts1990-1994
- Ts1994-1998
- Ts1998-2002
- Ts2002-2006

Second, change between time-slices is examined. Descriptions of change are incorporated with the description of the second of each pair of time-slices. This aims to answer the follow-on question *"What is the range condition trend doing?"*

Change is indicated by the symbol "∆". For example, when change between Ts1990-1994 and Ts1994-1998 is being examined, this is indicated by the abbreviated form ∆Ts1990-94/1994-98. Change in an index is similarly abbreviated, for example, ∆SRC Index 1990-94/1994-98. For further information on the calculation of the indices and construction of the time-slices, the reader is referred to Chapter 4. Classification of index values (and change values) was discussed in the previous section.

Third, where possible, inferences or presumptive cases for cause(s) of change are advanced, in an attempt to answer the third type of question mentioned earlier.

As part of the examination of the latest time-slice Ts2002-2006, a preliminary spatio-statistical analysis of sites partitioned into three different biophysical spatial entities is also presented. This endeavours to answer the second type of question mentioned above.

For convenience, the hierarchical SRC Indices framework, discussed and illustrated in Chapter 4, is shown again here as Figure 5.2 Further, it is suggested that reading of the following descriptions is best done in conjunction with the accompanying maps (Figures 5.3 – 5.25). However, please note that due to the plethora of maps required to depict each index in each time-slice and change between time-slices (at least 132 maps), most maps have not been included here. Whilst all of the SRC Index maps (four maps) and ∆SRC Index maps (three maps) are included here, only selected sub-index maps are included to show particular patterns or features of importance or interest.

5.4.2 Range Condition at Time-slice Ts1990-1994

For this early time-slice, there are only 55 sites for which the SRC Index could be calculated due to the paucity of LFA (Landscape Function Analysis) and SSC (Soil Surface Condition) field metrics captured at this time.

The *Shrubland Range Condition (SRC) Index* ranges from a minimum of 16.9 to a maximum of 63.7, with mean and median values of 25.3 and 24.7 respectively. Standard deviation (σ) is 6.7 but the frequency distribution is poorly defined normal due to the low number of sites. Most sites (Figure 5.3) have an SRC Index of less than 27.6 (“Fair Condition” or poorer) with only 12 sites having values indicating

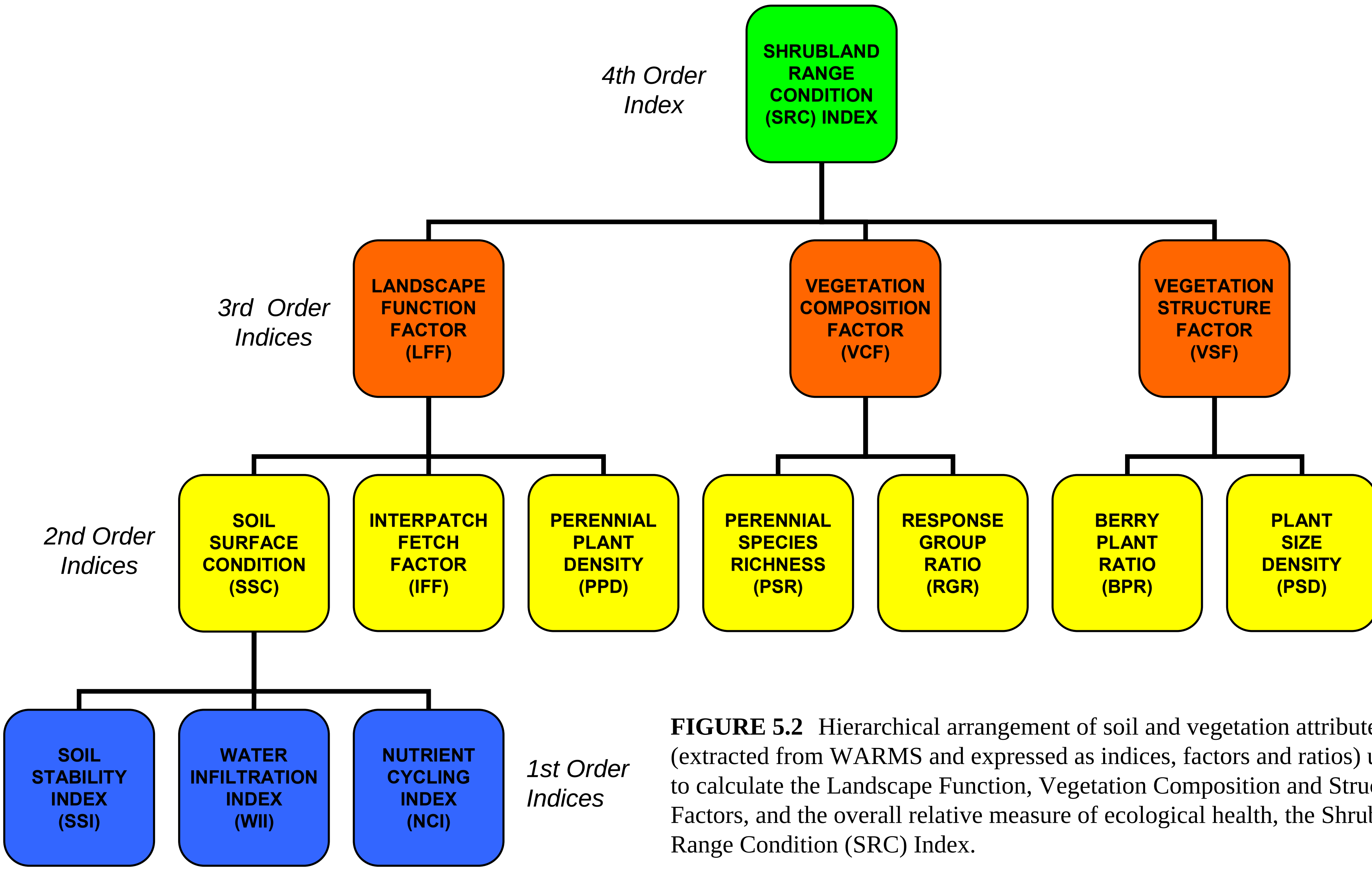


FIGURE 5.2 Hierarchical arrangement of soil and vegetation attributes (extracted from WARMS and expressed as indices, factors and ratios) used to calculate the Landscape Function, Vegetation Composition and Structure Factors, and the overall relative measure of ecological health, the Shrubland Range Condition (SRC) Index.

"Good Condition" or "Very Good Condition". Table 5.3 summarises basic statistics for the SRC Indices at this time.

Table 5.3 Basic statistics for the principal SRC Indices in time-slice Ts1990-1994.

INDEX	***SITES COUNT***	***MEAN***	***MINIMUM***	***MAXIMUM***	***VARIANCE (σ^2)***
SRC	55	25.3	16.9	63.7	44.6
LFF	55	6.4	5.6	7.3	0.1
VCF	55	12.5	6.2	16.6	4.6
VSF	55	6.4	2.7	43.0	34.3

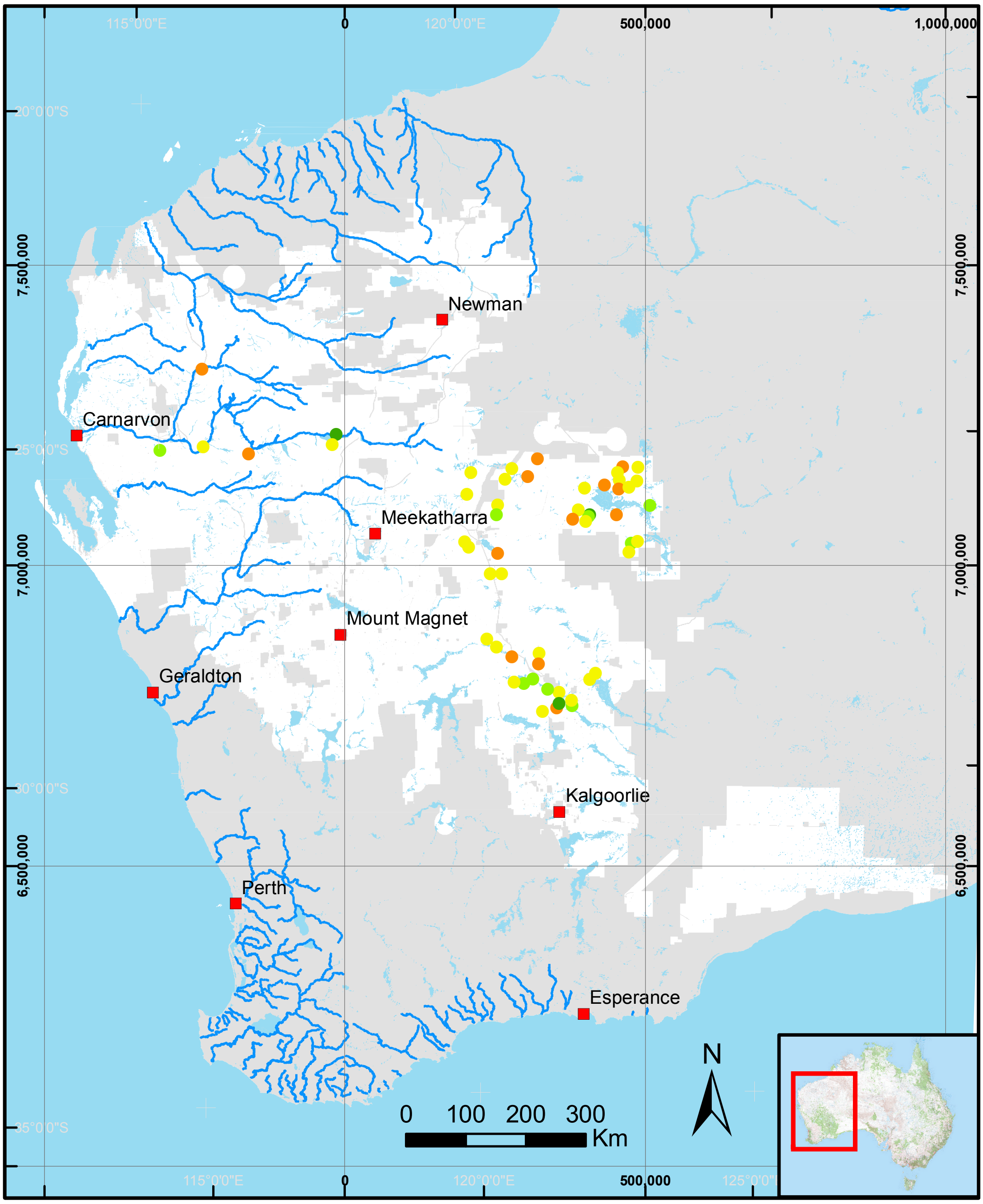
The sites in this time-slice occur in the vicinity of Leonora and northwest towards and just north of Wiluna, within the Murchison-1 IBRA subregion, and in the Lake Carnegie district to the east-northeast of Wiluna within the Gascoyne-2 IBRA subregion. A small number of sites also occur along the middle and upper reaches of the Ashburton River within the Gascoyne-3 IBRA subregion.

Apart from noting that most sites are in "Fair" or poorer condition (SRC Index ≤ 27.6), no distinct region-wide pattern or association is discernible due to the paucity of sites at this time.

In regard to the *Landscape Function Factor (LFF),* there are two contrasting groups of sites, and a scattering of other sites (a map of this index is not included). In the Leonora district, a group of sites show relatively high LFF values with five of the sites having "Very High" or "High" values, driven by high perennial plant density (PPD), stable soil surface (SSI) and properly functioning patch-interpatch resource capture (IFF) ability during this period (Ts1990-1994).

In contrast, a group of sites surrounding Lake Carnegie show generally much lower LFF values. Nine sites are classed as "Low" or "Very low". These sites are driven

Western Australian Rangeland Monitoring System (WARMS)



Legend

- Towns
- Major Rivers
- Lakes and Salt Lakes

SRC TS 1990-1994

SRC

- 13.08 - 15.60 Very Poor
- 15.61 - 21.60 Poor
- 21.61 - 27.60 Fair
- 27.61 - 33.60 Good
- 33.61 - 84.80 Very Good

Coordinate System: MGA 94 Zone 51

Southern Rangelands Range Condition (SRC Index) At Ts 1990 - 1994

Peter Russell

16 October 2007

Figure 5.3

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

C:\SRCGIS\MapDocuments\WARMS_RangeCondtionSRCIndexTS1990_94_MGAZ51_20071016.mxd

by very low perennial plant density (PPD), low soil nutrient cycling (NCI) and water infiltration (WII), and weakly functioning patch-interpatch resource capture (IFF).

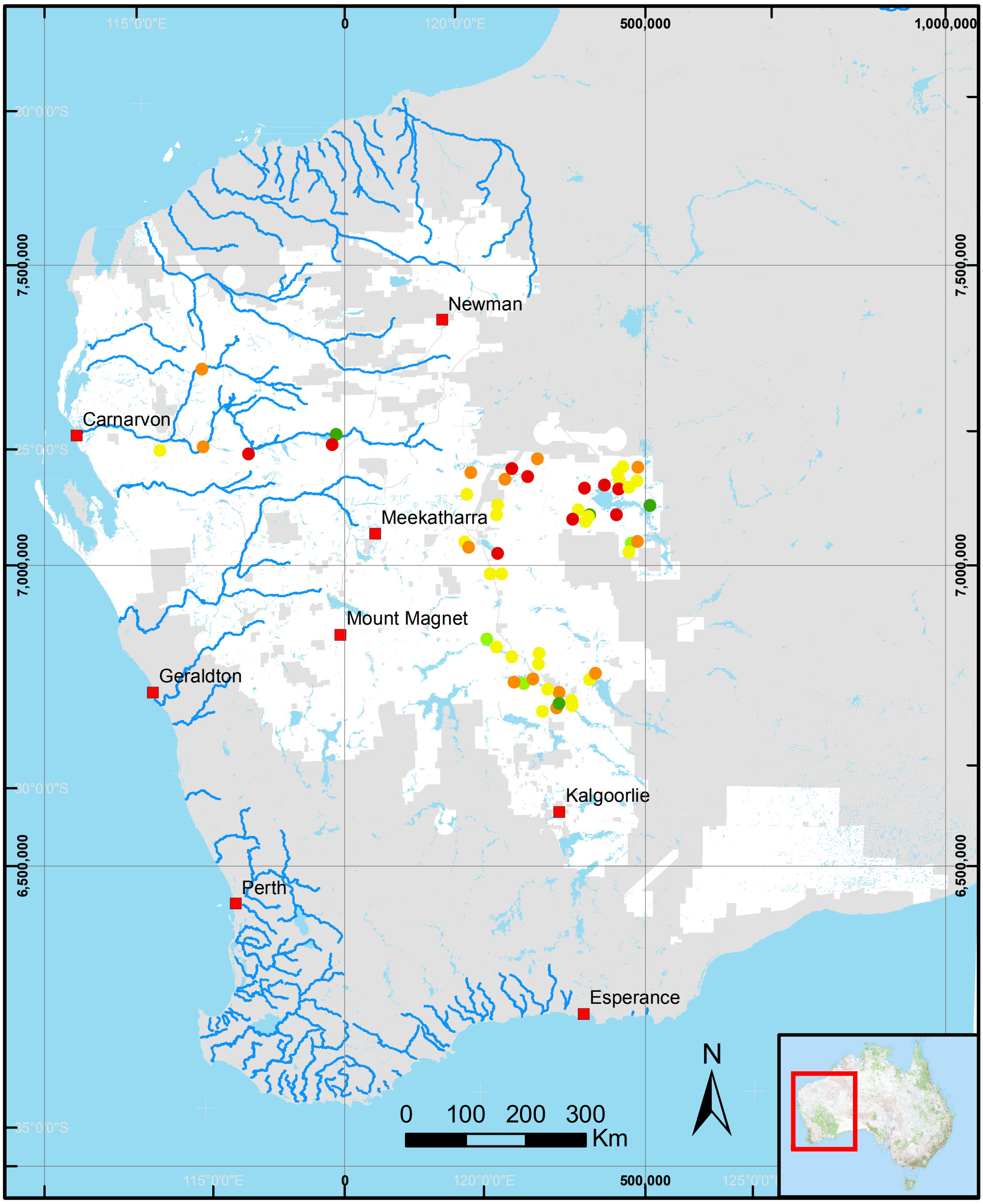
Five of the six sites along the Gascoyne River show “Moderate” or “Low” LFF values, for the same reasons given for the Lake Carnegie sites; one site is classed as “Very High”.

The pattern in regard to the *Vegetation Composition Factor (VCF)* (map of this index is not included) is similar to the LFF pattern but less pronounced. In the Leonora district, seven of the 17 sites show “High” or “Very High” VCF values, driven by high perennial species richness (PSR) and a beneficial mix of decreaser and increaser plants (RGR), and six sites show “Low” or “Very Low” values. The group of 19 sites surrounding Lake Carnegie show a mix of values between “High” and “Low” in contrast to their LFF values which were generally lower. The “High” value exhibited by six sites is driven by higher perennial species richness (PSR) and moderate ratio of decreaser and increaser plants (RGR).

The sites along the Gascoyne River have, apart from one site with “Low” VCF value (mainly driven by very low decreaser/increaser ratio), “Moderate” or “High” values.

The pattern of *Vegetation Structure Factor (VSF)* values in time-slice Ts1990-1994 (see Figure 5.4) reveals a clear geographic differentiation. Compared to sites in all other areas, the group of sites in the Leonora district generally have higher VSF values, with three sites classed as “High” or “Very High” and the majority (nine sites) classed as “Moderate”. In contrast, the remaining 38 sites in this time-slice occurring in the Lake Carnegie area, between Meekatharra and Lake Carnegie and along the Gascoyne River, show generally lower values indicative of very low numbers of berry-bearing plants (BPR) and reduced density of adult plants (PSD). Within the pattern of generally degraded sites (low LFF and VSF), seven sites have VSF values classed as “High” or “Very High”.

Western Australian Rangeland Monitoring System (WARMS)



Legend

- Towns
- Major Rivers
- Lakes and Salt Lakes

VSF TS 1990-1994

- 1.93 - 3.38 Very Low
- 3.39 - 4.40 Low
- 4.41 - 8.46 Moderate
- 8.47 - 13.54 High
- 13.55 - 64.74 Very High

Coordinate System: MGA 94 Zone 51

Southern Rangelands Vegetation Structure Factor (VSF) At Ts 1990 - 1994

Peter Russell

16 October 2007

Figure 5.4

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

C:\SRCGIS\MapDocuments\WARMS_VegetationStructureFactorVSF_TS1990_94_MGAZ51_20071016.mxd

The percentage of sites in each class for the principal indices for this time-slice is summarised in Table 5.4.

Table 5.4 Percentage of WARMS sites in each classification for the principal SRC Indices in time-slice Ts1990-1994.

INDEX	*"Very Poor" or "Very Low" (%)*	*"Poor" or "Low" (%)*	*"Fair" or "Moderate" (%)*	*"Good" or "High" (%)*	*"Very Good" or "Very High" (%)*
SRC	1.8	23.2	53.6	16.1	5.4
LFF	5.4	28.6	44.6	12.5	8.9
VCF	3.6	25.0	33.9	35.7	1.8
VSF	19.6	23.2	44.6	5.4	7.1

In summary, the SRC Index indicates that for Ts1990-1994, range condition was generally "Fair" or worse. 13 sites (23.2%) are shown as "Poor" condition and one (1.8%) as "Very Poor" condition at this time. The main indexical factors causing reduced range condition in the poorer sites appears to be the combination of lower VSF and LFF values rather than lower VCF values, indicating the presence of accelerated soil erosion and possibly the effect of fire at some sites.

5.4.3 Range Condition at Time-slice Ts1994-1998 and Change from Previous Ts.

For this time-slice, there are 342 sites for which the SRC Index could be calculated.

The *Shrubland Range Condition (SRC) Index* ranges from a minimum of 13.9 to a maximum of 81.7, a range greater than that shown by the previous time-slice. Mean and median values are 24.0 and 23.4 respectively with standard deviation (σ) of 5.4.

The frequency distribution is normal with slight positive skewness. Table 5.5 summarises basic statistics for the SRC Indices.

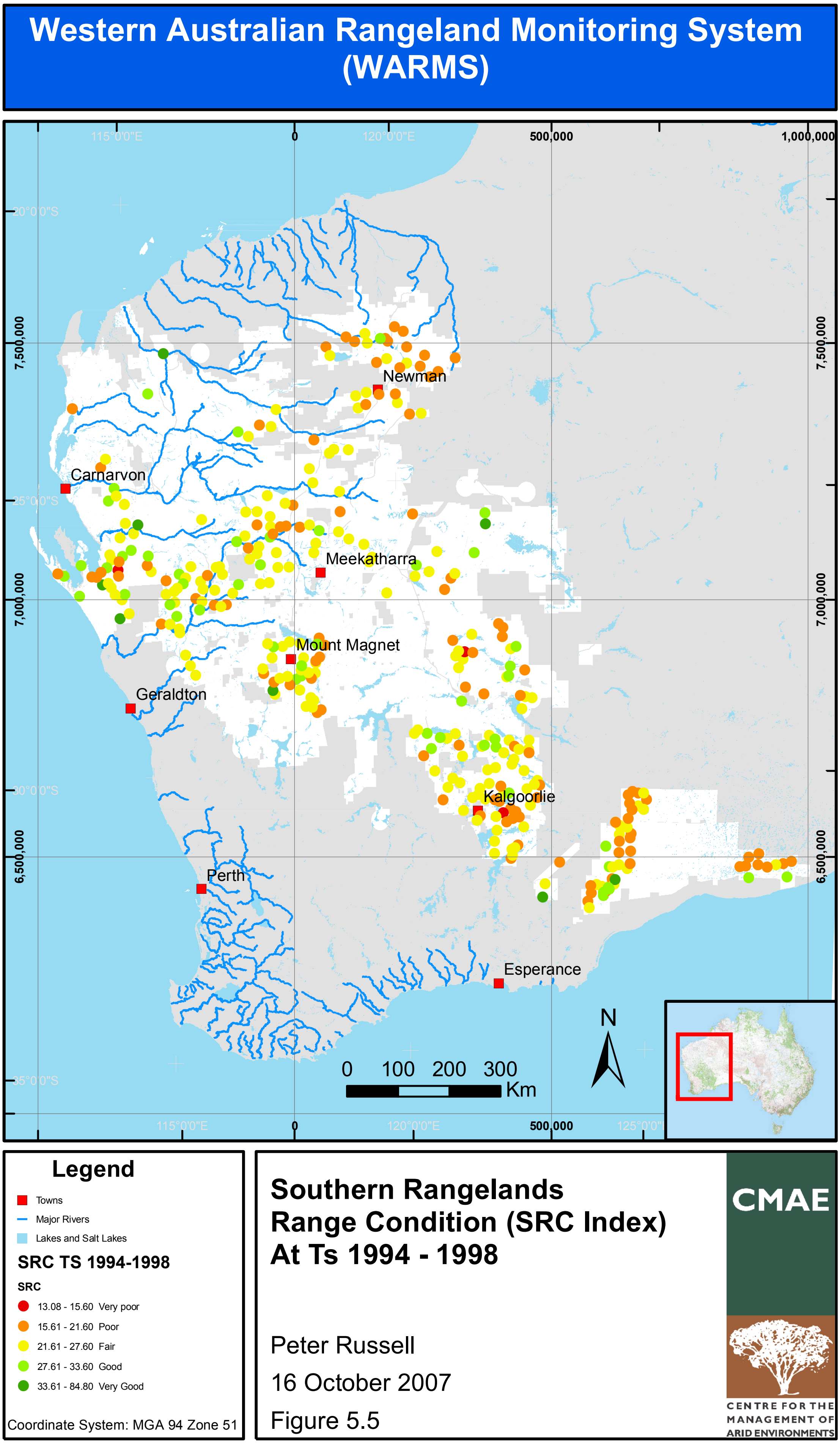
Table 5.5 Basic statistics for the SRC Indices in time-slice Ts1994-1998.

INDEX	*SITES COUNT*	*MEAN*	*MINIMUM*	*MAXIMUM*	*VARIANCE (σ^2)*
SRC	342	24.0	13.9	81.7	29.4
LFF	342	6.4	5.6	7.2	0.1
VCF	342	12.1	4.8	18.5	5.9
VSF	342	5.6	2.1	61.9	20.9

The geographic distribution of sites during this time-slice (Ts1994-1998) (see Figure 5.5) extends southwest from the southern Pilbara region through the upper Ashburton and Gascoyne regions to the Shark Bay area on the coast, thence southeast through the Murchison region to the Goldfields and eastwards into the Nullarbor region.

Within this extensive coverage, the *SRC Index* does not exhibit any clear shrubland-wide or region-wide pattern but does show more localised patterns. Overall, range condition was generally “Fair” to “Poor” at this time, with isolated sites or small clusters of sites in better condition. There are, however, several conspicuous clusters of sites showing evidence of generally poorer range condition, that is, sites with “Poor” or “Very Poor” classification. These clusters are located in the southern Pilbara in the vicinity of Newman, south of Newman in the upper Ashburton River, along the upper reaches of the Murchison River northwest of Meekatharra, south of the Wooramel River in the Shark Bay area, just east of Kalgoorlie and further east in the northern parts of Fraser Range and, finally, in the southern Nullarbor region.

At the other end of the range condition spectrum, there are small clusters of sites in “Good” or “Very Good” condition but these occur much less frequently and are less



C:\SRCGIS\MapDocuments\WARMS_RangeCondtionSRCIndexTS1994_98_MGAZ51_20071016.mxd

conspicuous in the overall pattern of weakened range condition during this time-slice.

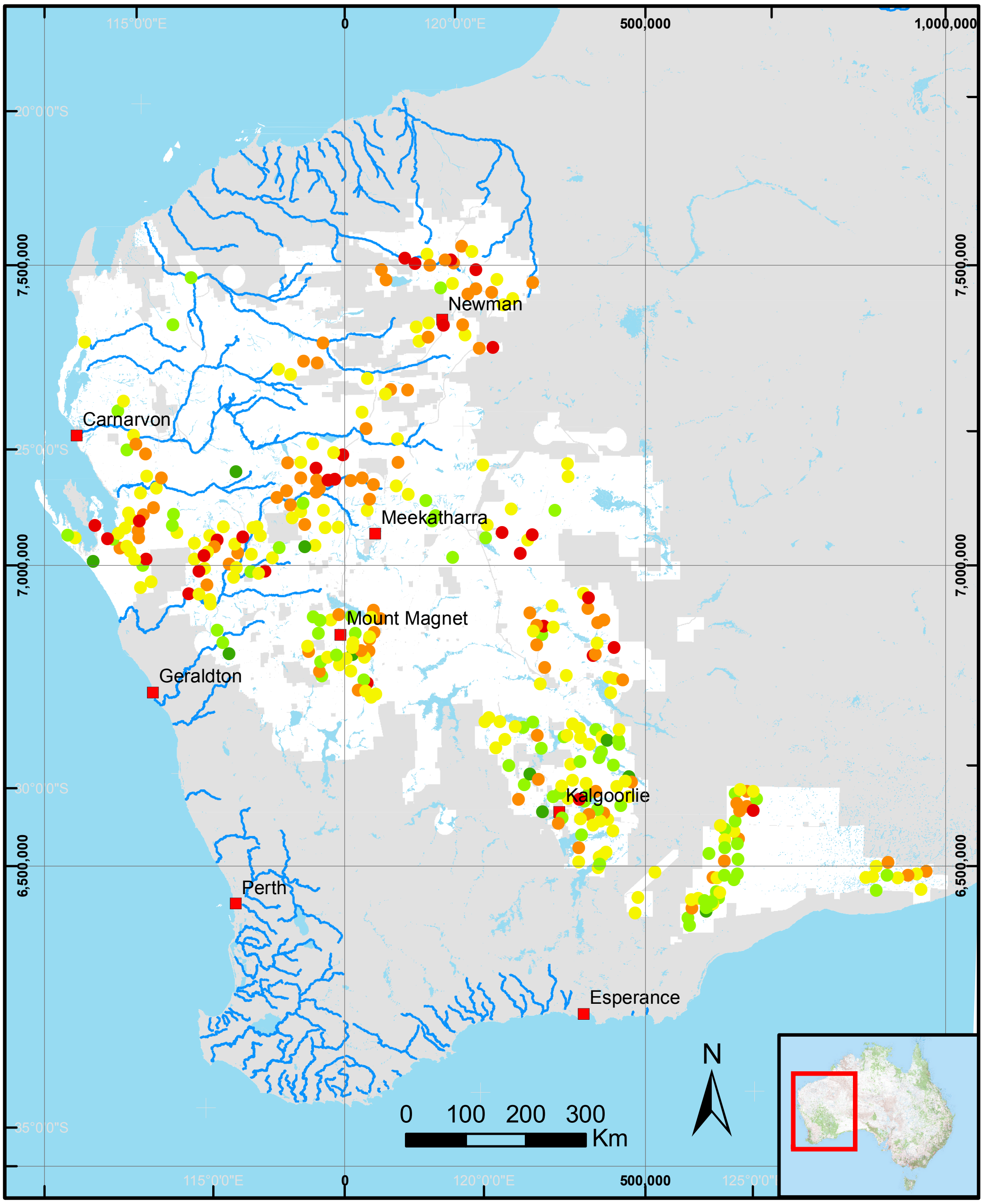
In contrast to the SRC Index, the *Landscape Function Factor (LFF)* (see Figure 5.6) exhibits a general increasing trend across the southern rangelands from northwest to southeast. Within this overall pattern, there are two conspicuous clusters of sites with “Low” or “Very Low” LFF values, driven by reduced perennial plant density (PPD) and soil surface condition (SSC). One cluster is located around Newman and the other along the upper reaches of the Murchison River northwest of Meekatharra. There are other smaller clusters of sites with low LFF values.

Consistent with the overall trend, clusters of sites with “High” or “Very High” LFF values occur in the Kalgoorlie area and in the Fraser Range-Southern Hills area between Kalgoorlie and the Nullarbor.

In regard to the *Vegetation Composition Factor (VCF)* (see Figure 5.7), three very conspicuous clusters of sites with “Low” or “Very Low” values in the southeastern parts of the shrublands occur in the Kalgoorlie area, Fraser Range-Southern Hills and Nullarbor. The Fraser Range-Southern Hills is notable for the complete absence of any site with “High” or “Very High” VCF values, driven by very low proportion of decreaser plants in the assemblage (RGR) and low species richness (PSR).

Sites in the remainder of the southern rangelands show an expected mix of “Moderate”, “High” and “Very High” values, with minor clusters of “Low” or “Very Low” value sites. An exception is the cluster north of Newman dominated by sites with “Fair” or lower VCF values, mainly driven by a low proportion of decreasers in the plant assemblage (RGR).

Western Australian Rangeland Monitoring System (WARMS)



Legend

- Towns
- Major Rivers
- Lakes and Salt Lakes

LFF TS 1994-1998

LFF

- 4.71 - 5.90 Very low
- 5.91 - 6.20 Low
- 6.21 - 6.60 Moderate
- 6.61 - 6.90 High
- 6.91 - 7.41 Very High

Coordinate System: MGA 94 Zone 51

Southern Rangelands Landscape Function Factor (LFF) At Ts 1994 - 1998

Peter Russell

16 October 2007

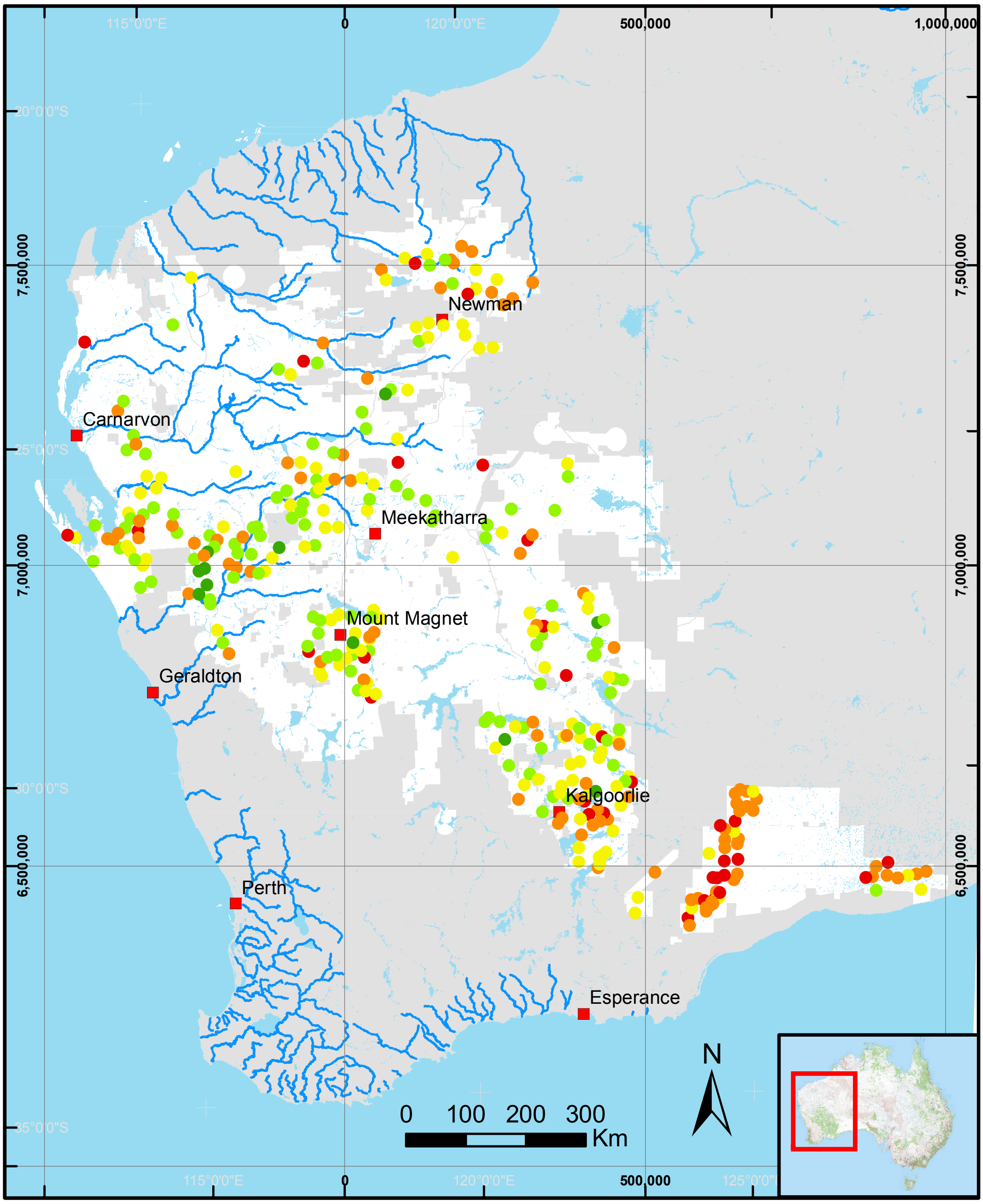
Figure 5.6

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

C:\SRCGIS\MapDocuments\WARMS_LandscapeFunctionFactorLFF_Ts1994_1998_MGAZ51_20071016.mxd

Western Australian Rangeland Monitoring System (WARMS)



Legend

- Towns
- Major Rivers
- Lakes and Salt Lakes

VCF TS 1994-1998

- 4.81 - 8.55 Very Low
- 8.56 - 11.05 Low
- 11.06 - 13.55 Moderate
- 13.56 - 16.05 High
- 16.06 - 18.50 Very High

Coordinate System: MGA 94 Zone 51

Southern Rangelands Vegetation Composition Factor (VCF) At Ts 1994 - 1998

Peter Russell

16 October 2007

Figure 5.7

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

C:\SRCGIS\MapDocuments\WARMS_VegetationCompositionFactorVCF_TS1994_1998_MGAZ51_20071016.mxd

In this time-slice (Ts1994-1998), the pattern exhibited by the *Vegetation Structure Factor (VSF)* (map not included) is conspicuous by the widespread dominance of "Moderate" or lower value sites. Notably, however, a cluster of sites in the Southern Hills area southeast of Kalgoorlie shows "Moderate" or higher values, driven by both a high proportion of adult plants in the assemblage (PSD) and high proportion of berry-bearing plants (BPR).

In summary, the SRC Index indicates that for the Ts 1994-1998 time-slice, range condition at WARMS sites was generally "Fair", with minor clusters of "Good" condition sites but offset by larger clusters of "Poor" sites, particularly in the southern Pilbara region and in the Fraser Range area. Table 5.6 summarises the proportion of sites in the southern rangelands in each class for the SRC index and its principal sub-indices.

Table 5.6 Percentage of WARMS sites in each classification for the principal SRC Indices in time-slice Ts1994-1998.

INDEX	***"Very Poor" or "Very Low" (%)***	***"Poor" or "Low" (%)***	***"Fair" or "Moderate" (%)***	***"Good" or "High" (%)***	***"Very Good" or "Very High" (%)***
SRC	1.2	32.6	49.3	14.6	2.3
LFF	9.0	24.5	42.0	21.6	2.9
VCF	9.3	26.2	31.2	29.7	3.2
VSF	0.3	21.3	64.3	10.2	3.8

In regard to the change in range condition from the previous time-slice to this time-slice (ΔTs1990-1994/1994-1998), the coverage of ΔSRC Index map data is very limited due to the paucity of sites common to both time-slices, due to the low number of sites in Ts1990-1994.

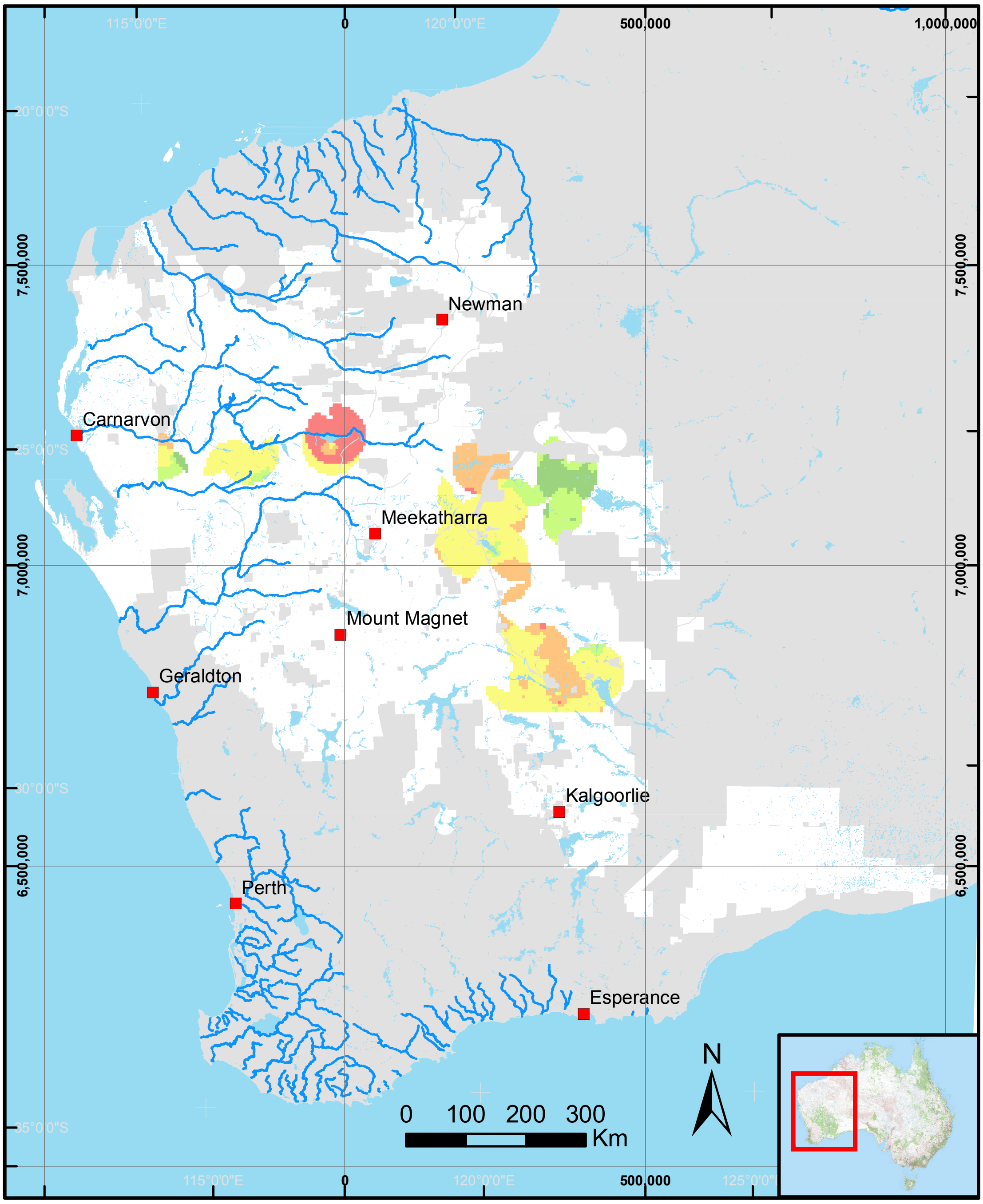
Figure 5.8 shows the ∆SRC Index pattern. The coverage forms a discontinuous arc from the Leonora area northwards to the Lake Carnegie-Meekatharra area then westwards to cover parts of the Gascoyne River catchment. The coverage is too limited to reveal shrubland-wide trends (if present) but does show two areas of substantial change, and areas of less substantial change. Approximately 55% of the coverage shows nil or minimal change in range condition, whilst approximately 25% shows negative change and only 20% shows a positive change.

The principal area of substantial negative change (deltaSRC Index < - 8.8) occurred in the lower-upper reaches of the Gascoyne River. The change in range condition here is driven by moderate reduction in all three principal sub-indices LFF, VSF and VCF, collectively contributing to the substantial adverse change. The change is putatively attributed to high herbivore grazing pressure, affecting the condition of both the vegetation and soil surface. Stock numbers have historically been very high in this part of the shrublands.

Other areas of negative change in range condition occur in the interior endorheic Salt Lake Basin. These areas form a discontinuous belt, interspersed with areas of minimal change, trending south-southeast from north of Wiluna in the Lake Nabberu area to the Leonora district. The moderate negative change in this belt is driven mainly by a reduction in LFF values, with some contribution by reductions in VSF and VCF values. This is indicative of increased soil erosion but the causal agent is not clear from the data. Although herbivore grazing pressure is implicated, an additional agent is possibly storm events associated with the extremely high rainfall in this area in the October 1994 – September 1998 period which followed a very dry period October 1992 – September 1994.

The main area of positive change in range condition is situated just to the west of Lake Carnegie. Here, the change is driven by a marked increase in VCF values,

Western Australian Rangeland Monitoring System (WARMS)



Legend

- Towns
- Lakes and Salt Lakes
- Major Rivers

Delta SRC Ts90-94 / Ts94-98

- -61.3 - -8.8 Substantial Negative Change
- -8.7 - -2.6 Moderate Negative Change
- -2.5 - 3.6 Nil or Minor Change
- 3.7 - 9.8 Moderate Positive Change
- 9.9 - 46.6 Substantial Positive Change

Coordinate System: MGA 94 Zone 51

Southern Rangelands Range Condition Change (delta SRC Index) Ts 1990-1994 / Ts 1994-1998

Peter Russell

16 October 2007

Figure 5.8

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

C:\SRCGIS\MapDocuments\WARMS_ChangeInRangeConditionDeltaSRC_Ts90_94to94_98_MGAZ51_20071016.mxd

some increase in VSF values and lesser increase in LFF values. The change has occurred in an area that was in generally “Fair” condition. A marked reduction in herbivore grazing pressure is thought to be the principal reason for the positive change.

5.4.4 Range Condition at Time-slice Ts1998-2002 and Change from Previous Ts.

For this time-slice, there are 797 sites (see Figure 5.9) for which the SRC Indices could be calculated and they are well distributed throughout the southern rangelands with the exception of two areas, the southern Pilbara north of Newman and east of Kalgoorlie in the Southern Hills-Fraser Range area. Notably, this is the first time-slice where most of the sites in the western Nullarbor are mapped.

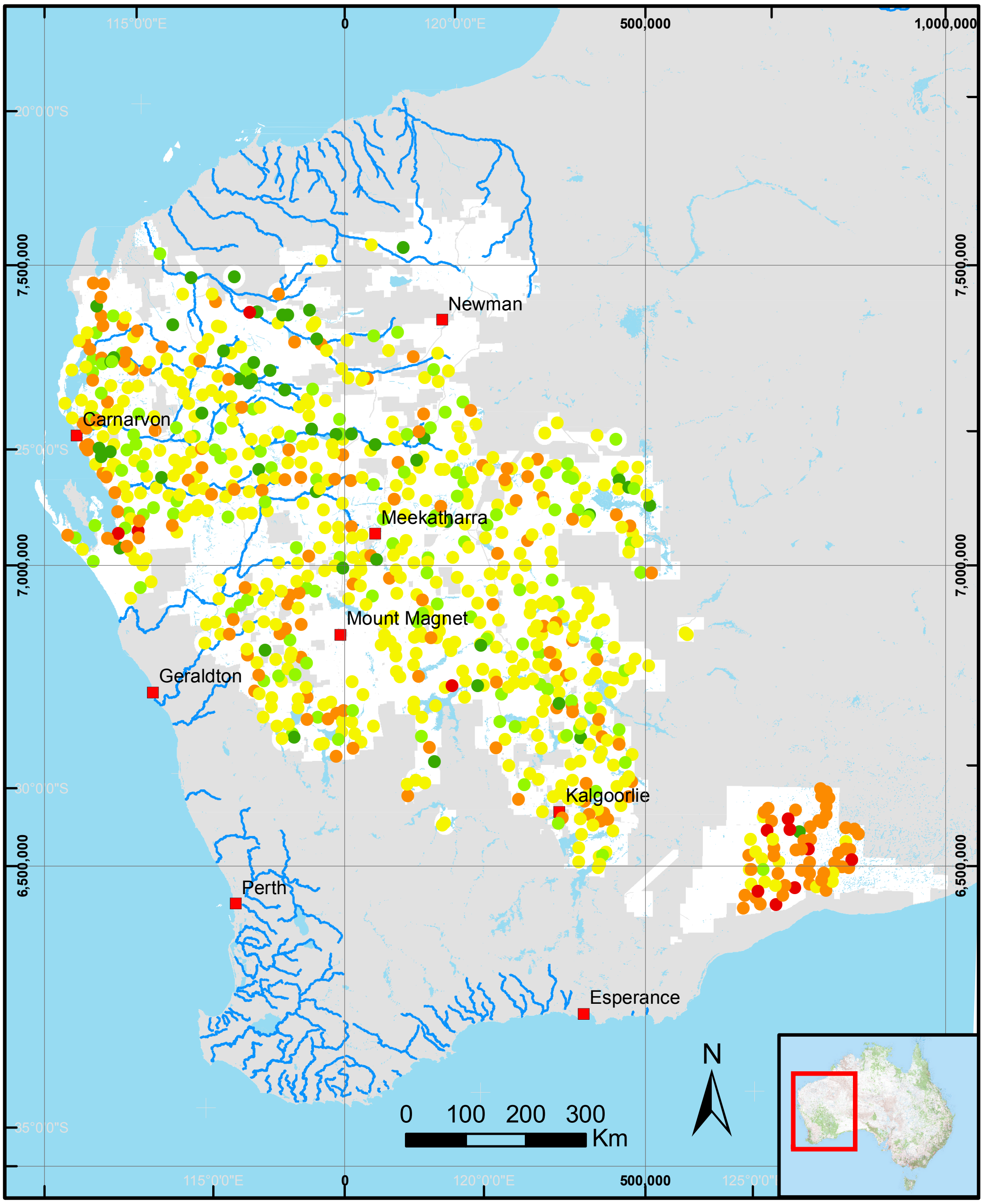
Shrubland Range Condition (SRC) Index values range from a minimum of 13.1 to a maximum of 84.8 (the largest range of all time-slices) with mean and median values of 24.9 and 23.9 respectively. Standard deviation is 6.5 and the frequency distribution is normal with positive skewness. Table 5.7 summarises basic statistics for the SRC Indices.

Table 5.7 Basic statistics for the SRC Indices in time-slice Ts1998-2002.

INDEX	***SITES COUNT***	***MEAN***	***MINIMUM***	***MAXIMUM***	***VARIANCE (σ^2)***
SRC	797	24.9	13.1	84.8	41.6
LFF	797	6.5	5.1	7.4	0.1
VCF	797	12.5	4.9	17.6	6.4
VSF	797	6.0	1.9	64.7	29.5

The pattern of *SRC Index* values (Figure 5.9) in this time-slice is dominated by sites in “Fair” condition throughout most of the southern rangelands, punctuated by individual sites or small clusters of sites in either “Poor”/”Very Poor” or “Good”/“Very

Western Australian Rangeland Monitoring System (WARMS)



Legend

- Towns
- Major Rivers
- Lakes and Salt Lakes

SRC TS 1998-2002

SRC

- 13.08 - 15.60 Very Poor
- 15.61 - 21.60 Poor
- 21.61 - 27.60 Fair
- 27.61 - 33.60 Good
- 33.61 - 84.80 Very Good

Coordinate System: MGA 94 Zone 51

Southern Rangelands Range Condition (SRC Index) At Ts 1998 - 2002

Peter Russell

16 October 2007

Figure 5.9

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

C:\SRCGIS\MapDocuments\WARMS_RangeCondtionSRCIndexTS1998_2002_MGAZ51_20071016.mxd

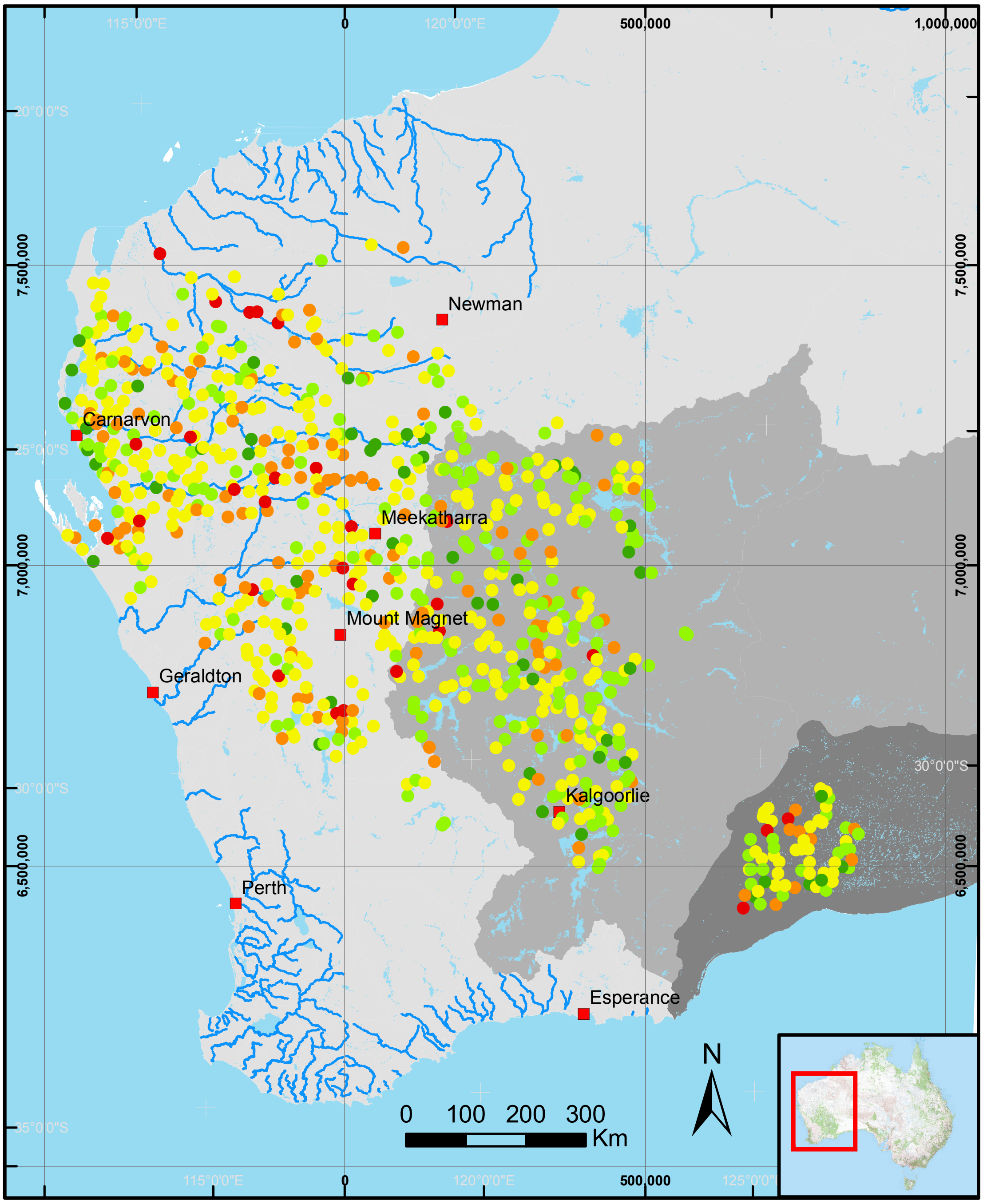
Good" condition. There is a very weakly expressed general reduction in range condition from northwest to southeast but this trend may be more apparent than real since there are conspicuous clusters of sites which confound or confuse the overall pattern. These confounding clusters fall at both ends of the range condition spectrum. At the poor end, there are two major clusters dominated by "Poor" and "Very Poor" sites. The first forms a discontinuous belt along the coast, trending south from Exmouth Gulf to the Shark Bay area. This linear cluster tends to 'link up' with several smaller, less well defined clusters spatially associated with drainages. It is mainly low VCF values which drive the lower SRC Index values in this area.

The second major confounding cluster of sites occurs on the Nullarbor. This large, very conspicuous group of sites in poor condition, with only a few sites in "Fair" condition and two in "Good" or better condition, is driven by low Vegetation Composition Factor (VCF) values, in turn caused by very low proportions of decreasers in the plant assemblage (RGR) and generally low species richness (PSR). The low species richness, in comparison to almost all other vegetation assemblages in the southern rangelands, is a notable feature of the Nullarbor chenopod shrubland.

At the good end of the range condition spectrum, several discontinuous linear clusters dominated by sites in "Very Good" condition are located along the middle to lower reaches of the Ashburton River, and to the south along the upper reaches of the Gascoyne River and its major northern tributary, the Lyons River. In regard to the Ashburton River, unfortunately the good condition sites are interspersed with sites in "Very Poor" to "Fair" condition, indicative of degradation, reflected in low VCF and LFF values. These indices are examined further below.

The overall spatial pattern exhibited by the *Landscape Function Factor (LFF)* is a general increase in values across the southern rangelands from west to east (Figure 5.10). This pattern appears to be related to river catchment/drainage basin base-

Western Australian Rangeland Monitoring System (WARMS)



Legend

LFF TS 1998-2002

- 4.71 - 5.90 Very Low
- 5.91 - 6.20 Low
- 6.21 - 6.60 Moderate
- 6.61 - 6.90 High
- 6.91 - 7.41 Very high

Drainage Basin Type

- Exorheic Drainage
- Arheic Region
- Endorheic Drainage
- Endorheic Drainage

Coordinate System: MGA 94 Zone 51

Southern Rangelands Landscape Function Factor (LFF) At Ts 1998 - 2002

Peter Russell

16 October 2007

Figure 5.10

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

C:\SRCGIS\MapDocuments\WARMS_LandscapeFunctionFactorLFFDrainageType_Ts1998_2002_MGAZ51_20071016.mxd levels. Sites located in the eastern parts, mainly within the endorheic basins, generally have higher LFF values, driven by more effective resource capture (indicated by higher IFF values), higher perennial plant density (PPD) and relatively stable soil surfaces (SSI), indicating relatively less active erosion in the salt lake country dominated by mulga *(Acacia aneura)* hardpan plains.

In contrast, the sites located in the exorheic catchments in the western parts of the southern rangelands are affected by greater rates of soil erosion during this time-slice, indicated by lower perennial plant density (PPD) and reduced resource capture (IFF).

Within this general pattern, there are several conspicuous clusters of low LFF value sites. The most northerly cluster occurs along the middle to lower reaches of the Ashburton River. The major cluster, however, is located to the south occupying parts of the Gascoyne, Wooramel and Murchison catchments and extending westward to the Shark Bay area. The “Low” LFF values at sites in the upper Murchison River are driven mainly by very low perennial plant density (PPD).

Contrasting with the low LFF value clusters is a cluster of sites in the upper reaches of the Gascoyne River (Three Rivers district) dominated by “Very High” LFF values, indicative of overall low rates of soil erosion. These sites have high soil stability and water infiltration rates (high SSC values) and, in parts, very high perennial plant density (PPD) combining to minimise erosion.

Sites in the Nullarbor region, dominated by “Moderate” to “High” LFF values, indicate overall low rates of soil erosion, but this benefit is offset by very low perennial plant density (PPD) at many sites.

Apart from two conspicuous clusters, the pattern exhibited by the *Vegetation Composition Factor (VCF)* is a reasonably uniform mix of “Low” to “High” value sites with a scattering of “Very Low” and “Very High” sites (map not included). However, excluding the coastal zone sites, there is a weakly developed spatial trend of decreasing VCF values across the southern rangelands from northwest to southeast at this time (Ts1998-2002). This weak trend is mirrored more strongly by the Vegetation Structure Factor, examined below.

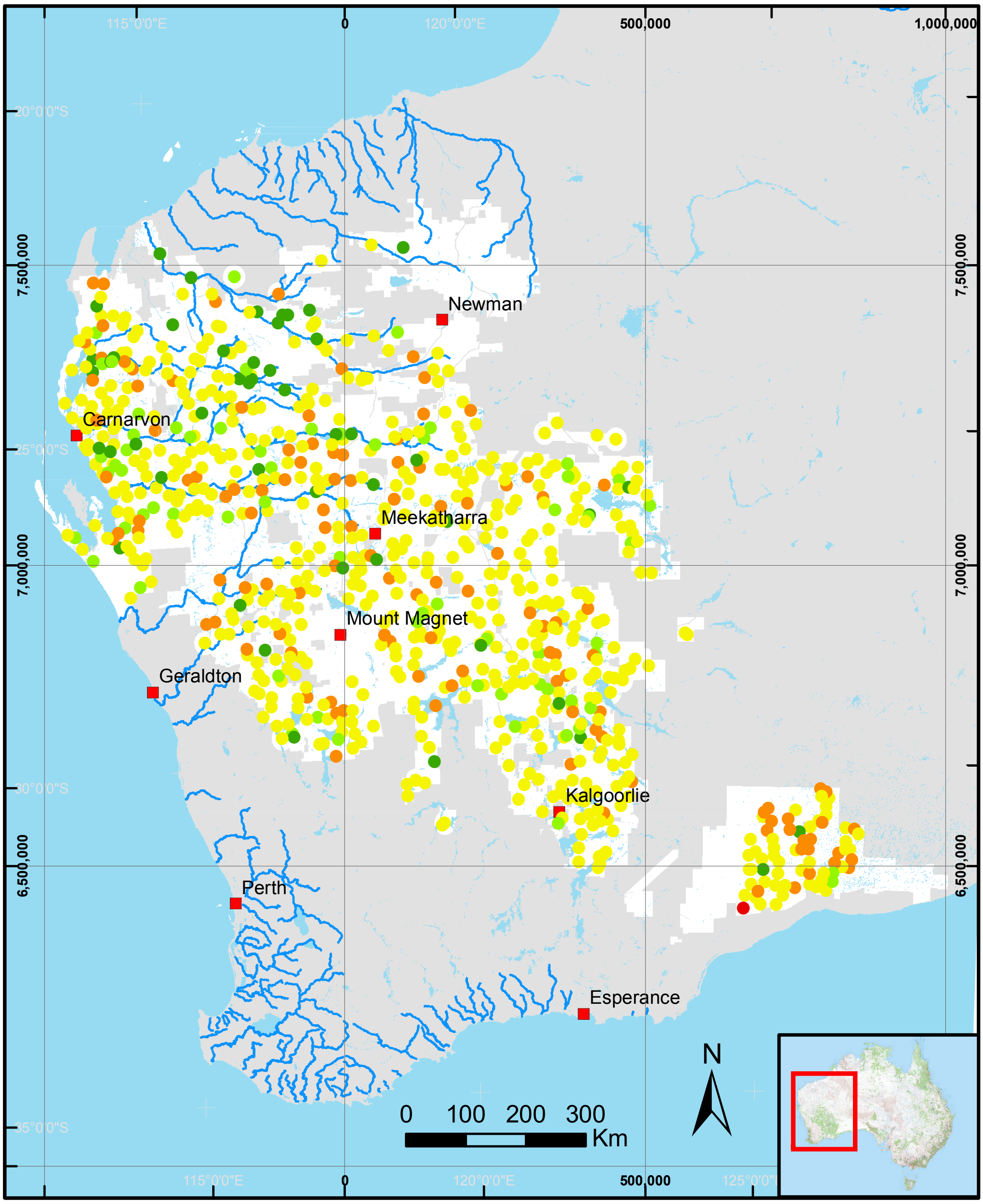
The most conspicuous cluster of sites is on the Nullarbor. Here, almost all sites have “Low” or “Very Low” VCF values, driven by very low species richness (PSR) and low proportion of decreasers in the vegetation assemblage (RGR). The low species richness is characteristic of much of the chenopod shrubland in this region. Earlier, Mitchell *et al.* (1988) attributed this depauperate characteristic mainly to the widespread occurrence of shallow, stony, highly calcareous soils.

The cluster of coastal sites, dominated by “Low” VCF values, extends as an ill-defined, discontinuous belt south from Exmouth Gulf to the Shark Bay area. Here, the low VCF values are driven by very low species richness (PSR).

Finally, it is worth noting that a number of sites along the middle to lower reaches of the Ashburton River exhibit “Low” or “Very Low” VCF values, driven in this situation almost entirely by very low proportions of palatable decreaser plants in the vegetation assemblage (RGR). Species richness (PSR) at these sites is generally moderate to high.

Although the pattern shown by the *Vegetation Structure Factor (VSF)* is dominated by sites with “Moderate” values, there is a reasonably pronounced spatial trend of decreasing values from northwest to southeast across the southern rangelands in this time-slice (Figure 5.11). This trend is engendered by a number of small clusters of sites with “High” and “Very High” values in the Ashburton River, Gascoyne River and Lyons River catchments, which contrast with the dominance of sites in the Nullarbor region with “Moderate” or lower VSF values.

Western Australian Rangeland Monitoring System (WARMS)



Legend

- Towns
- Major Rivers
- Lakes and Salt Lakes

VSF TS 1998-2002

- <1.93 Very Low
- 1.94 - 3.38 Low
- 3.39 - 8.46 Moderate
- 8.47 - 13.54 High
- 13.55 - 64.74 Very High

Coordinate System: MGA 94 Zone 51

Southern Rangelands Vegetation Structure Factor (VSF) At Ts 1998 - 2002

Peter Russell

16 October 2007

Figure 5.11

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

C:\SRCGIS\MapDocuments\WARMS_VegetationStructureFactorVSF_TS1998_2002_MGAZ51_20071016.mxd

Almost all sites with “High” or “Very High” VSF values in the northern parts of the southern rangelands have significantly high proportions of berry-bearing plants (BPR) in their vegetation assemblages, and in some cases a high proportion of adult plants (PSD). The Nullarbor sites, particularly in the eastern parts, frequently have no berry-bearing plants in the vegetation assemblage. The ecological significance of berry-bearing plants is discussed in Chapter 4.

In summary, it is apparent that several indices show region-wide patterns or spatial trends. The overall spatial trend of range condition (SRC Index) for the Ts1998-2002 time-slice is a slight reduction from northwest to southeast, culminating in the large number of poor condition sites on the Nullarbor. Interestingly, however, the soil erosion spatial trend, interpreted from the Landscape Function Factor (LFF) (Figure 5.10) and likely to be related to catchment base-levels, is contrary to both the vegetation composition (VCF) and vegetation structure (VSF) (Figure 5.11) trends.

Table 5.8 summarises the proportion of sites in the southern rangelands in each class for each of the SRC indices discussed above.

Table 5.8 Percentage of WARMS sites in each classification for the principal SRC Indices in time-slice Ts1998-2002.

INDEX	***“Very Poor” or “Very Low” (%)***	***“Poor” or “Low” (%)***	***“Fair” or “Moderate” (%)***	***“Good” or “High” (%)***	***“Very Good” or “Very High” (%)***
SRC	1.5	22.0	55.0	15.4	6.1
LFF	3.6	15.3	47.4	27.0	6.8
VCF	8.0	17.9	36.5	33.0	4.6
VSF	0.1	14.8	70.9	8.0	6.1

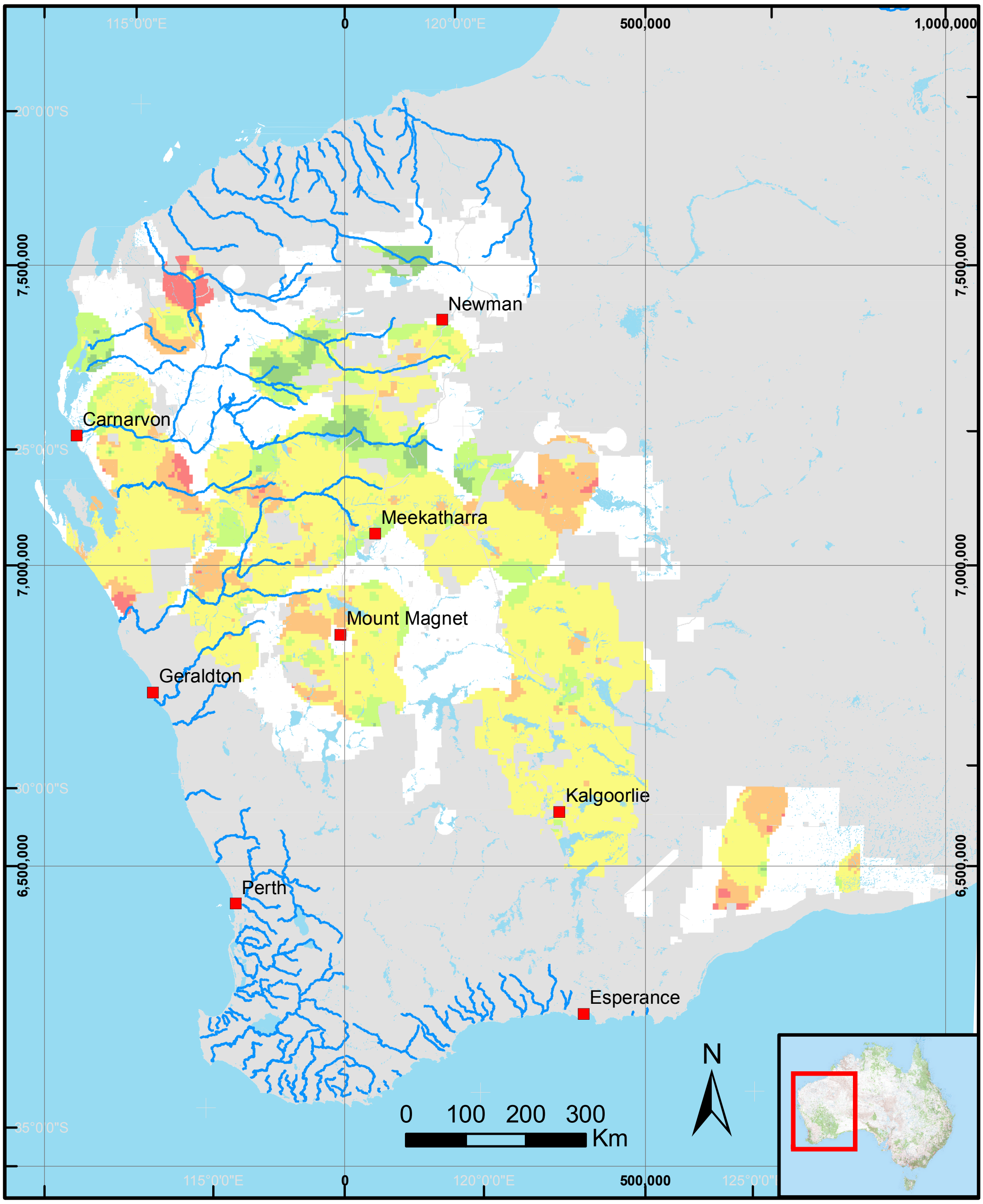
In regard to the change in range condition from the previous time-slice to this time-slice, the coverage of ∆SRC Index map data is considerably more extensive than that for the previous change period. Figure 5.12 shows the coverage for ∆Ts1994-1998/1998-2002, which in this change period extends from the southern Pilbara including much of the upper catchments of the Ashburton and Lyons Rivers, the upper and lower (but not middle) parts of the Gascoyne River catchment and all of the Wooramel and Murchison River catchments. There is complete coverage of the Mt Magnet district, substantial coverage of the Goldfields region, but only the western part of the Nullarbor region is included.

Approximately 75% of the area of coverage shows nil or minimal change in range condition from Ts1994-1998 to Ts1998-2002. Approximately equal proportions underwent negative or positive change. Whilst the following discussion focuses on change in range condition, the reader needs to be mindful that an indication of "No change" is not indicative of the status of actual range condition. For example, an area in poor condition that does not change is still in poor condition and, likewise, an area in good condition remains in good condition if unchanged.

The largest areas of change mainly occur in the northern parts of the southern rangelands. This is part of a region-wide trend of declining areal extent and magnitude of change from north to south. The Goldfields region shows remarkably little change during this period, as does the Meekatharra district.

The area showing the greatest decline in range condition (Figure 5.12) is situated in the Henry River sub-catchment of the Ashburton River catchment. Here the change is driven by a reduction in the value of all three principal sub-indices: LFF, VSF and VCF. This is indicative of long-term high herbivore grazing pressure, and contrasts strikingly with other areas in the southern Pilbara which show substantial improvement in range condition in this period (∆Ts1994-1998/1998-2002).

Western Australian Rangeland Monitoring System (WARMS)



Legend

- Towns
- Lakes and Salt Lakes
- Major Rivers

Delta SRC Ts94-98 / Ts98-02

- -61.3 - -8.8 Substantial Negative Change
- -8.7 - -2.6 Moderate Negative Change
- -2.5 - 3.6 Nil or Minor Change
- 3.7 - 9.8 Moderate Positive Change
- 9.9 - 46.6 Substantial Positive Change

Coordinate System: MGA 94 Zone 51

Southern Rangelands Range Condition Change (delta SRC Index) Ts 1994-1998 / Ts 1998-2002

Peter Russell

16 October 2007

Figure 5.12

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

C:\SRCGIS\MapDocuments\WARMS_ChangeInRangeConditionDeltaSRC_Ts94_98to98_02_MGAZ51_20071016.mxd

Two other areas of substantial decline in range condition, although smaller in area than the Henry River area, are nevertheless significant because they feature again in the examination of ∆Ts1998-2002/2002-2006. The most northerly of these two areas is located in the Wooramel River catchment, in the lower-middle reaches, stretching north-northwest from the river. The change in SRC Index values is driven mainly by a decline in VSF values. The reason for the change is not obvious but is examined again in the next ∆Ts.

The second area of substantial decline is situated close to Kalbarri just north of the mouth of the Murchison River. Here the decline in SRC Index values is driven by moderate declines in the three sub-indices LFF, VSF and VCF. This is indicative of long-term high herbivore grazing pressure.

Areas of moderate decline in range condition are scattered throughout the catchments of the Wooramel, Murchison and Yarra Monger Rivers, just west of Lake Carnegie in the Salt Lake Basin and in the western Nullarbor region.

The areas of substantial improvement in range condition during this period occur in the upper reaches of the Fortescue River, upper-middle reaches of the Gascoyne River merging with the upper reaches of the Lyons River, and the upper reaches of the Murchison River. In all areas, but particularly in the upper reaches of the Gascoyne River, the increased SRC Index values are driven by a marked increase in the LFF values, indicating substantial improvement in functional relationships between the vegetation and soil. This area is examined again in the next ∆Ts.

5.4.5 Range Condition at Time-slice Ts2002-2006 and Change from Previous Ts.

For this time-slice, there are 624 sites for which the SRC indices could be calculated. Values of the *Shrubland Range Condition (SRC) Index* range from 13.4 to 74.1 with mean and median values of 24.3 and 23.6 respectively. Standard deviation is 5.6. Table 5.9 summarises basic statistics for the principal SRC Indices.

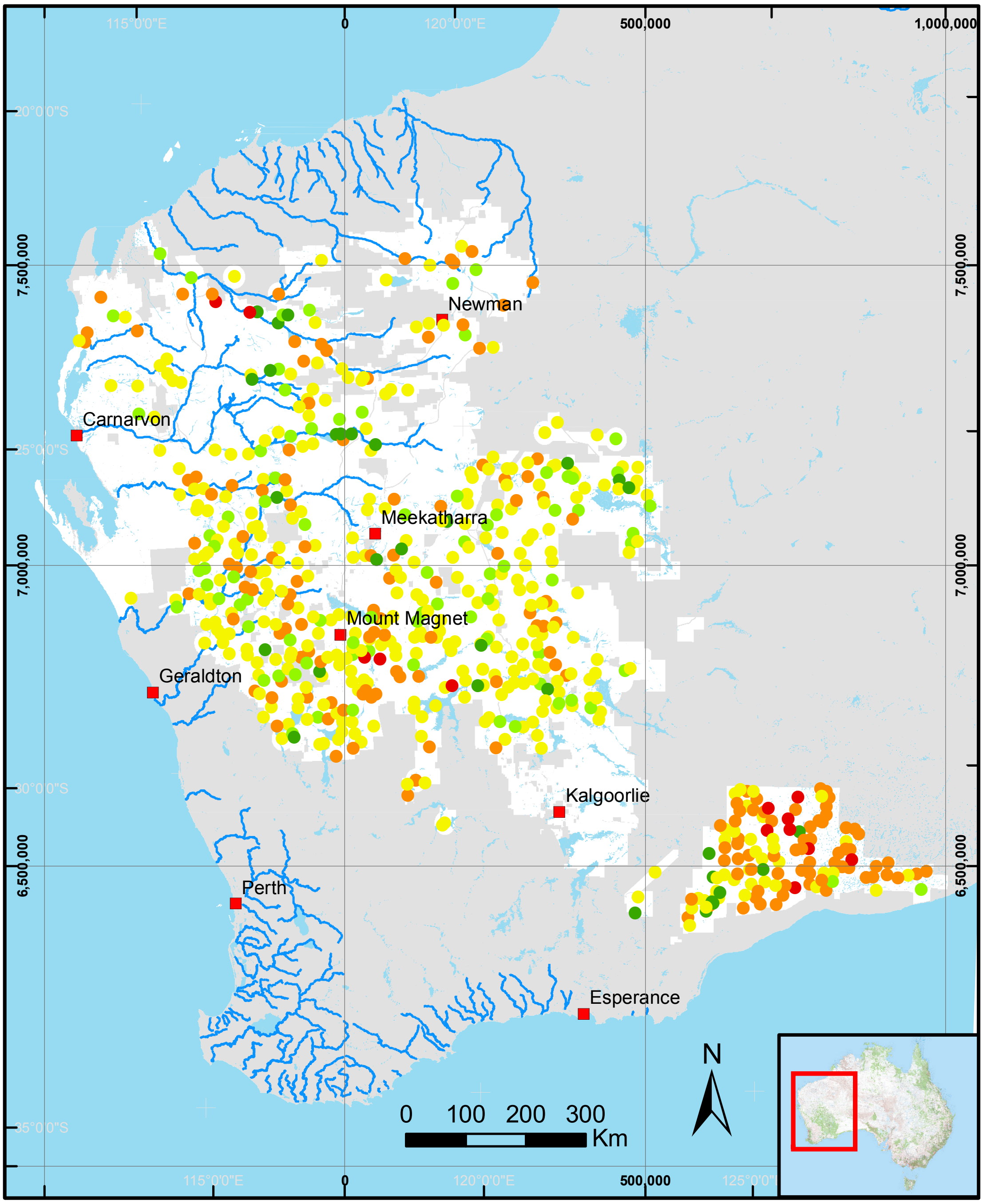
Table 5.9 Basic statistics for the SRC Indices in time-slice Ts2002-2006.

INDEX	***SITES COUNT***	***MEAN***	***MINIMUM***	***MAXIMUM***	***VARIANCE (σ^2)***
SRC	624	24.3	13.4	74.1	31.4
LFF	624	6.4	4.7	7.3	0.1
VCF	624	12.1	4.8	16.9	6.5
VSF	624	5.9	2.1	53.9	22.9

The geographic distribution of sites at this time (Ts2002-2006) extends south from the southern Pilbara region through the Ashburton, Gascoyne, Murchison and northern Goldfields regions (Figure 5. 13). A gap separates a large group of sites covering all of the pastoral properties in the western Nullarbor.

Within this extensive coverage, the SRC Index does not exhibit a clear shrubland-wide spatial trend but does contain more localised patterns. Apart from the Nullarbor region (considered below), range condition is generally “Fair” at this time, with small clusters of sites in poorer condition, mainly in the southwest parts of the Murchison region in the vicinity of Mount Magnet township. There are, however, conspicuous clusters of sites in “Good” or better condition in the middle reaches of the Ashburton River, upper Lyons River and upper reaches of the Gascoyne River. A high degree of variability in range condition is noticeable along the Ashburton River where sites in “Good” or better condition are interspersed with sites in “Poor” or “Very Poor” condition. The better condition sites are driven mainly by higher

Western Australian Rangeland Monitoring System (WARMS)



Legend

- Towns
- Major Rivers
- Lakes and Salt Lakes

SRC TS 2002-2006

SRC

- 13.08 - 15.60 Very Poor
- 15.61 - 21.60 Poor
- 21.61 - 27.60 Fair
- 27.61 - 33.60 Good
- 33.61 - 84.80 Very good

Coordinate System: MGA 94 Zone 51

Southern Rangelands Range Condition (SRC Index) At Ts 2002 - 2006

Peter Russell

16 October 2007

Figure 5.13

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

C:\SRCGIS\MapDocuments\WARMS_RangeCondtionSRCIndexTS2002_2006_MGAZ51_20071016.mxd

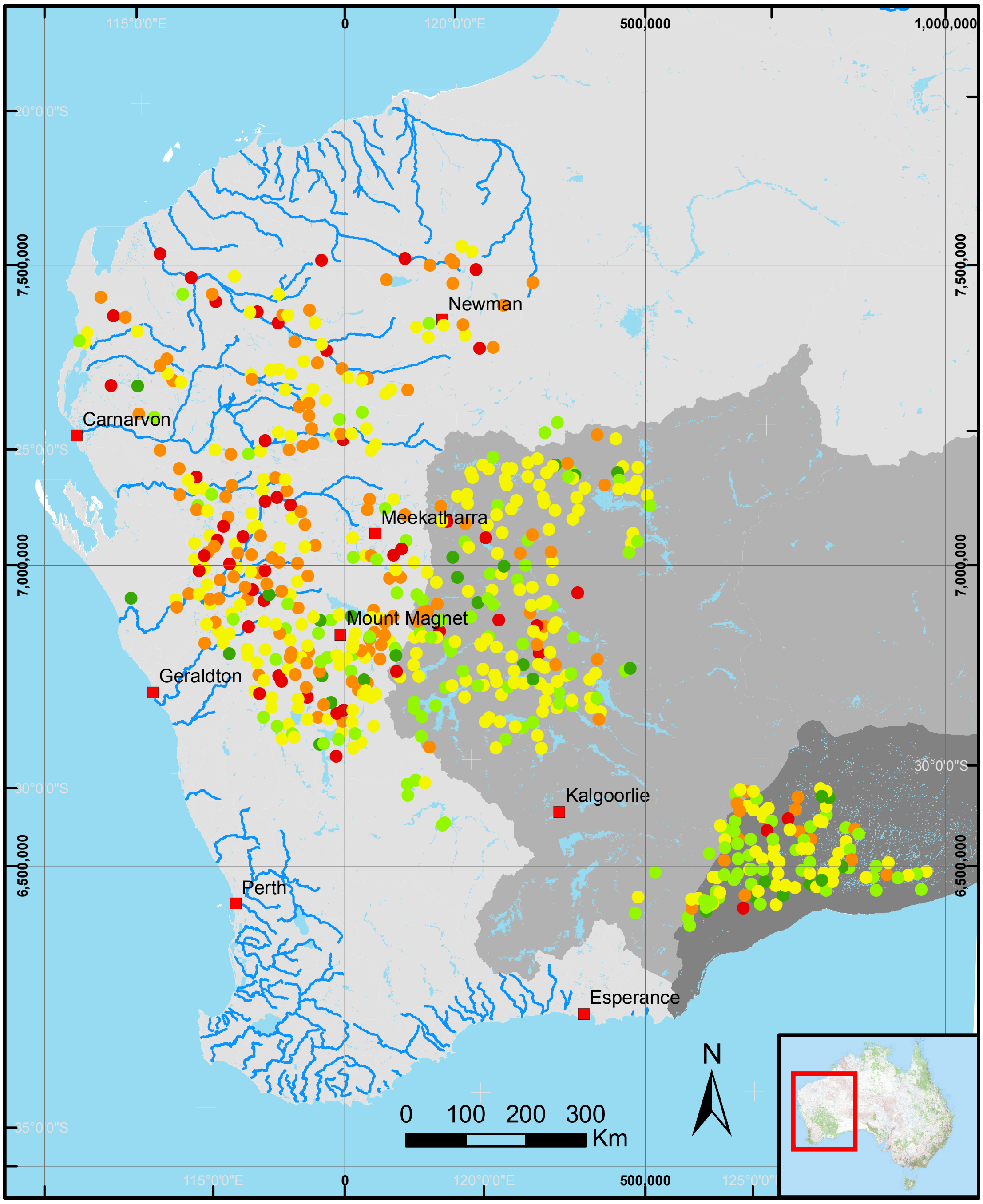
vegetation structural and compositional complexity but the Landscape Function Factor (LFF) tends to be lower than expected, indicating the presence accelerated soil erosion that has not yet directly affected the vegetation. However, the nearby sites in "Poor" or "Very Poor" condition show signs of more severe soil erosion (low LFF) which, in conjunction with other related drivers of change, has affected the vegetation (low VCF and VSF). A number of single, isolated sites in "Very Good" condition are scattered throughout the region.

In regard to the Nullarbor region, the SRC Index shows a tendency to decrease from the southwestern parts to the northern and eastern parts. The sites in "Very Poor" condition here, in contrast to the "Very Poor" sites along the Ashburton River, are driven by low VCF and VSF values rather than low LFF values. This is indicative of low rates of soil erosion, offset by a reduction in the compositional and structural complexity of the vegetation.

Across the entire southern rangelands, the *Landscape Function Factor (LFF)* reveals a very clear differentiation of sites into two groups (Figure 5.14) and is the same pattern revealed in the previous time-slice (Ts1998-2002). In general, sites located in exorheic drainage catchments have "Moderate" and lower LFF values, in contrast to sites located in endorheic catchments and arheic areas (Nullarbor) which have "Moderate" or higher values. This differentiation is indicative of a fundamental difference in erosion regimes, engendered by different drainage base-levels. Of the exorheic catchments, the Murchison and Wooramel appear to be the most severely affected by soil erosion, followed by the Ashburton and Gascoyne catchments. Most sites in these catchments are characterised by low values for the Soil Surface Condition (SSC), Interpatch Fetch Factor (IFF) and Perennial Plant Density (PPD) indices.

Within the endorheic catchments, scattered amongst the predominantly "Moderate" to "Very High" value sites are sites with "Very Low" LFF values. In these cases, the

Western Australian Rangeland Monitoring System (WARMS)



Legend

LFF TS 2002-2006

- 4.71 - 5.90 Very Low
- 5.91 - 6.20 Low
- 6.21 - 6.60 Moderate
- 6.61 - 6.90 High
- 6.91 - 7.28 Very High

Drainage Basin Type

- Exorheic Drainage
- Arheic Region
- Endorheic Drainage
- Endorheic Drainage

Coordinate System: MGA 94 Zone 51

Southern Rangelands Landscape Function Factor (LFF) At Ts 2002 - 2006

Peter Russell

16 October 2007

Figure 5.14

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

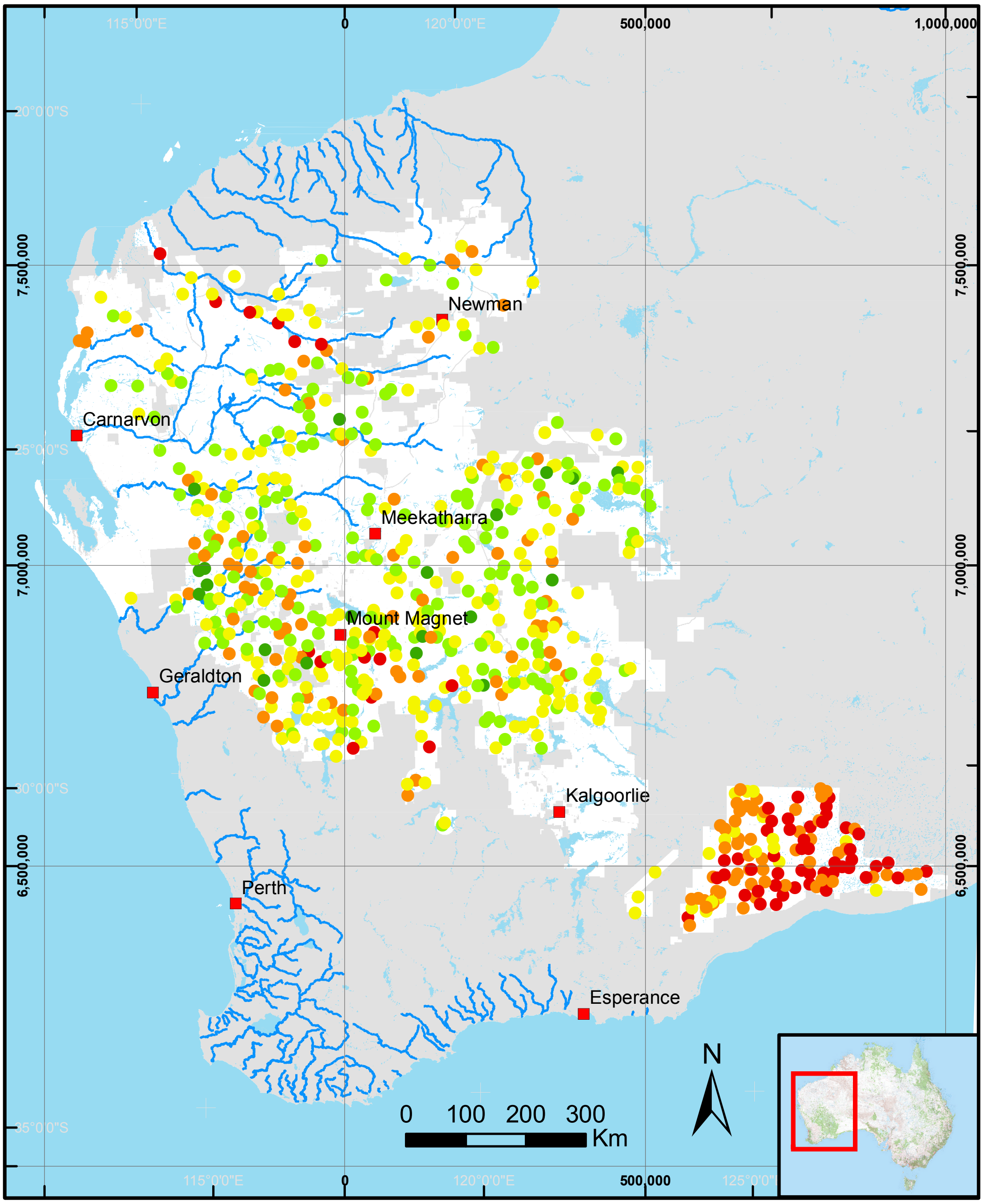
C:\SRCGIS\MapDocuments\WARMS_LandscapeFunctionFactorLFFDrainageType_Ts2002_2006_MGAZ51_20071016.mxd low values are driven mainly by very low perennial plant density (PPD) and, in some cases, by low patch-interpatch ratios (IFF). In rare cases, Soil Surface Condition (SSC) is also very low.

The arheic Nullarbor region shows a higher proportion of sites with “Moderate” or higher LFF values than is shown by any other region in the southern rangelands at this time (Ts2002-2006). This, as was noted for the previous time-slice, is indicative of low rates of soil erosion. There is a weakly developed spatial trend, confounded in part by a central belt of sites with “Moderate” values, of decreasing LFF values from south to north.

In regard to the *Vegetation Composition Factor (VCF),* a pattern very different from that shown by the LFF and VSF indices is apparent (Figure 5.15). The Nullarbor region is conspicuous for its complete absence of sites with “High” and “Very High” VCF values. Here, the low values are driven by low to very low perennial species richness (PSR) and low proportions of palatable decreaser plants (RGR) in the vegetation assemblage. These characteristics are now almost ubiquitous across the Nullarbor, as was noted for the previous time-slice (Ts1998-2002) and by Mitchell *et al.* (1988) from their range inventory and condition survey in 1974.

For the remainder of the southern rangelands, the VCF values are generally “Moderate” to “High” with scattered “Very High”, “Low” and “Very Low” sites. In addition, there are two clusters of sites worthy of mention. The first of these is a cluster of about eight sites extending northwards approximately 60km from the lower-middle reaches of the Murchison River, located just to the east of a belt of claypans. This cluster is conspicuous because of the occurrence of four sites with “Very High” VCF values and several other sites with “High” values, within a broader catchment area with a high proportion of “Low” value sites. The high value sites here are driven by very high species richness (PSR) at sites generally located in rough hill and lateritic breakaway country of low pastoral grazing value. Herbivore

Western Australian Rangeland Monitoring System (WARMS)



Legend

- Towns
- Major Rivers
- Lakes and Salt Lakes

VCF TS 2002-2006

- 4.81 - 8.55 Very Low
- 8.56 - 11.05 Low
- 11.06 - 13.55 Moderate
- 13.56 - 16.05 High
- 16.06 - 16.90 Very High

Coordinate System: MGA 94 Zone 51

Southern Rangelands Vegetation Composition Factor (VCF) At Ts 2002 - 2006

Peter Russell

16 October 2007

Figure 5.15

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

C:\SRCGIS\MapDocuments\WARMS_VegetationCompositionFactorVCF_TS2002_2006_MGAZ51_20071016.mxd grazing pressure appears to be very low here, although given the rough terrain, one would expect a large number of feral goats.

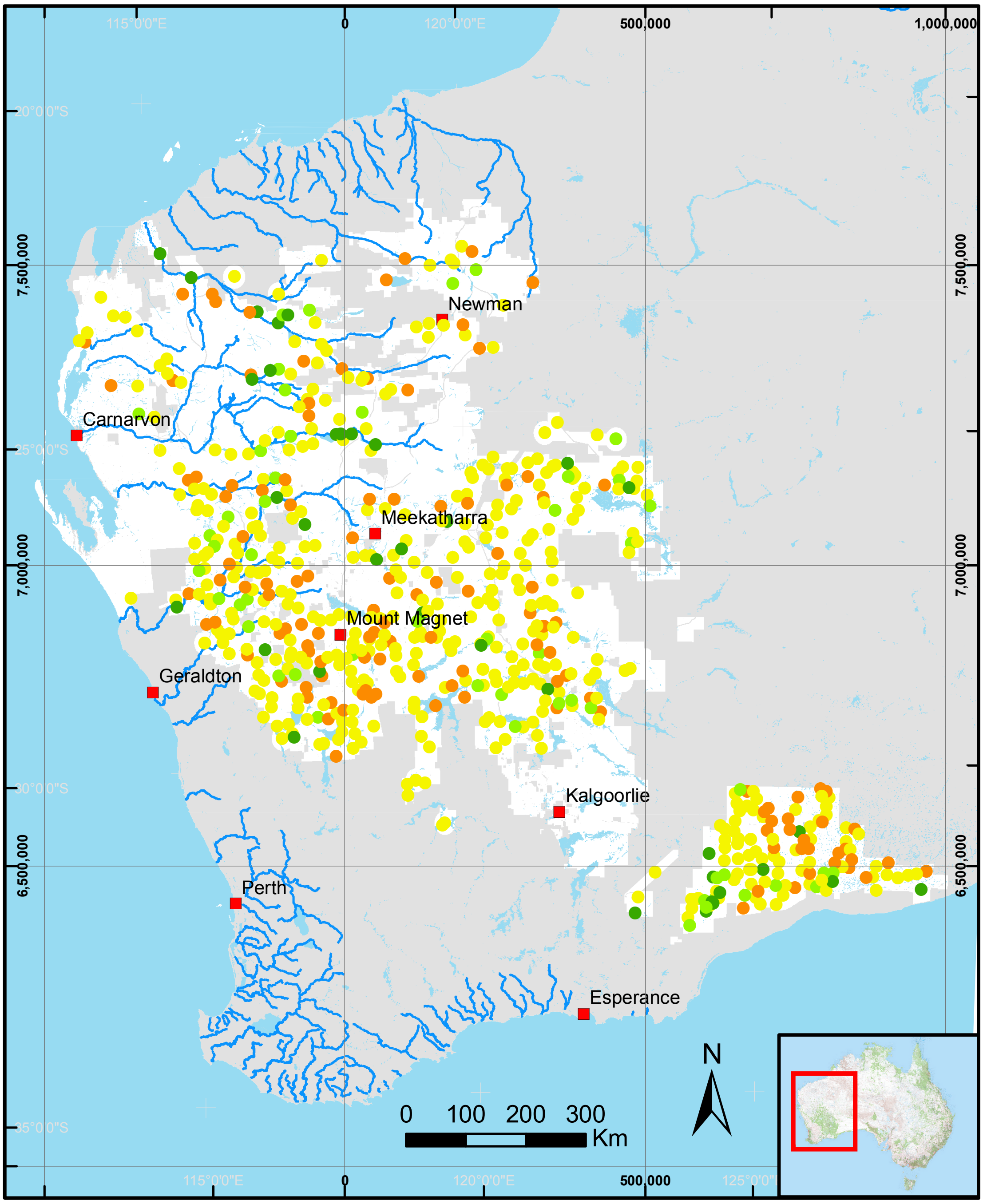
The second cluster, dominated by sites with “Very Low” VCF values, occurs along the middle to lower reaches of the Ashburton River. In this case, the low VCF values are driven by very low proportions of palatable decreaser plants (RGR) and low species richness (PSR) in the vegetation assemblages. The low VCF values here, matched with low LFF values noted earlier, indicate the presence of accelerated soil erosion and high herbivore grazing pressure.

In regard to the *Vegetation Structure Factor (VSF)* (see figure 5.16), the overall southern rangelands pattern is remarkably uniform, dominated by sites of “Moderate” value. However, there are several intra-catchment/intra-region patterns and trends worth noting at this time (Ts2002-2006).

The Nullarbor region shows a clear spatial trend of decreasing VSF values from west to east. This trend is driven by a distinct reduction in the proportion of berry-bearing plants (BPR) and a general but not ubiquitous reduction in the proportion of mature plants (PSD) in the vegetation assemblage. The combination of indexical factors here is indicative of depauperate bush (shrub) clumps. It is surmised that the cause is not soil erosion but a high level of herbivory.

In other regions of the southern rangelands, small clusters of sites with “Very High” and “High” VSF values occur in parts of the Gascoyne and Ashburton catchments. These clusters are conspicuous in an area otherwise dominated by “Moderate” to “Low” value sites, and here the higher values are driven by a combination of high proportions of berry-bearing plants and mature plants in the vegetation assemblages. This situation, contrary to the northeastern and eastern Nullarbor situation, is indicative of intact shrub clumps hosting a mixture of plant species, and greater population viability.

Western Australian Rangeland Monitoring System (WARMS)



Legend

- Towns
- Major Rivers
- Lakes and Salt Lakes

VSF TS 2002-2006

- 1.93 Very low
- 1.94 - 3.38 Low
- 3.39 - 8.46 Moderate
- 8.47 - 13.54 High
- 13.55 - 64.74 Very High

Coordinate System: MGA 94 Zone 51

Southern Rangelands Vegetation Structure Factor (VSF) At Ts 2002 - 2006

Peter Russell

16 October 2007

Figure 5.16

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

C:\SRCGIS\MapDocuments\WARMS_VegetationStructureFactorVSF_TS2002_2006_MGAZ51_20071016.mxd

Table 5.10 below summarises the proportion of sites in the southern rangelands in each class for each of the SRC indices discussed above.

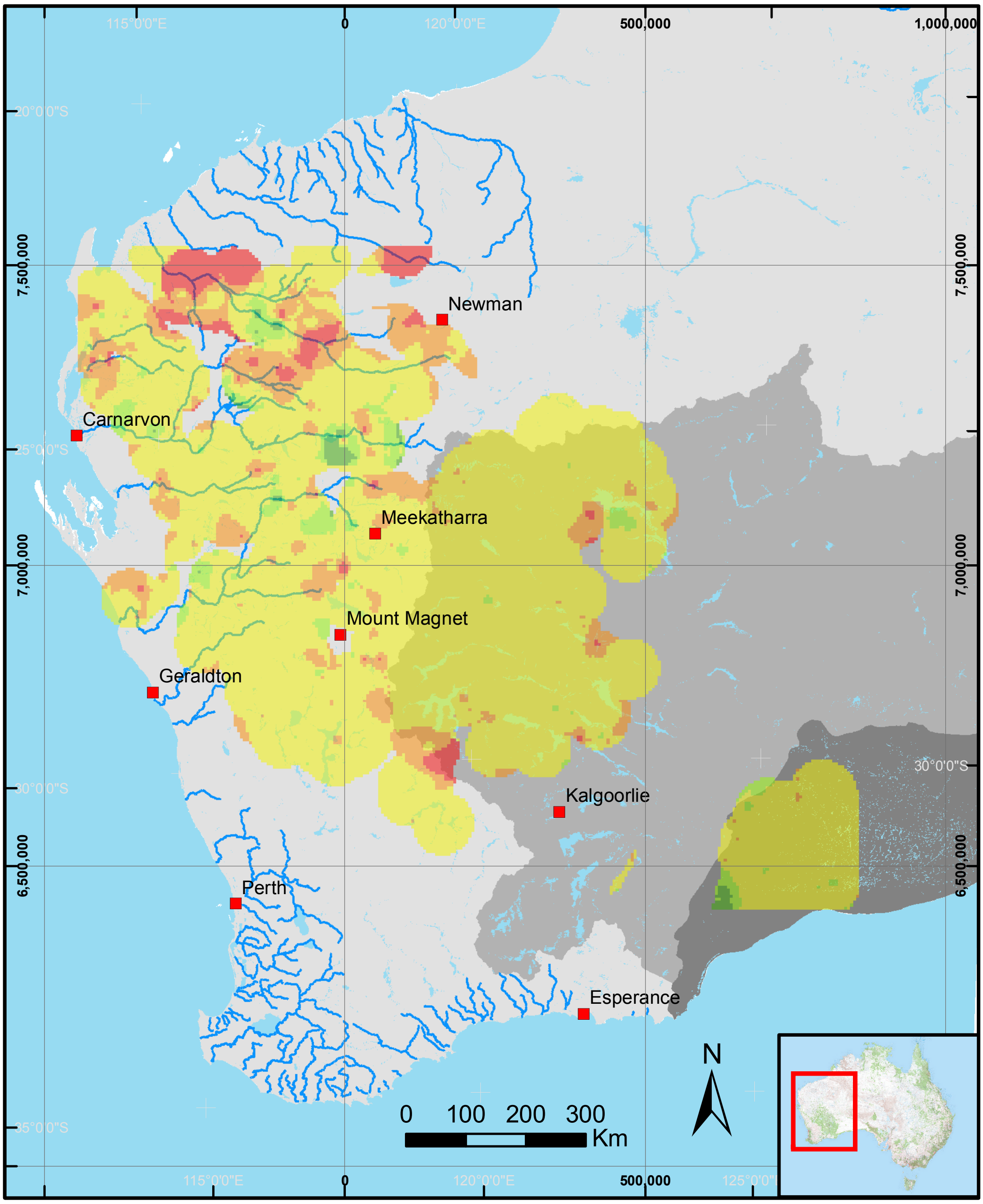
Table 5.10 Percentage of WARMS sites in each classification for the principal SRC Indices in time-slice Ts2002-2006.

INDEX	***"Very Poor" or "Very Low" (%)***	***"Poor" or "Low" (%)***	***"Fair" or "Moderate" (%)***	***"Good" or "High" (%)***	***"Very Good" or "Very High" (%)***
SRC	2.2	26.6	53.3	13.0	5.0
LFF	7.7	21.5	44.7	21.3	4.8
VCF	9.9	21.3	36.9	28.7	3.2
VSF	0.2	20.0	65.6	8.5	5.8

In regard to the change in range condition (∆SRC Index) from the previous time-slice to this time-slice (∆Ts1998-2002/2002-2006), the mapped coverage of ∆SRC Index data is as extensive as for the previous change period. Figure 5.17 shows the coverage. There is almost complete coverage from the southern Pilbara region through to the Goldfields region, and the Nullarbor. The areas not covered during this period include the coastal strip from Carnarvon to Shark Bay, the far-eastern parts of the southern Pilbara and upper-most part of the Gascoyne River catchment, the Kalgoorlie district (southern Goldfields) and small portions at the western and eastern extremities of the Nullarbor region.

As was found for the previous change period, the Nullarbor and most of the northern Goldfields from just north of Kalgoorlie northwards to well north of Lake Carnegie, show little change. This is part of a clear, broad shrubland-wide trend of generally decreasing change, in both areal extent and magnitude of change, from northwest to southeast. This pattern was also observed for the previous change period.

Western Australian Rangeland Monitoring System (WARMS)



Legend

Delta SRC Ts98-02 / Ts02-06

- -61.3 - -8.8 Substantial Negative Change
- -8.7- -2.6 Moderate Negative Change
- -2.5 - 3.6 Nil or Minor Change
- 3.7 - 9.8 Moderate Positive Change
- 9.9 - 46.6 Substantial Positive Change

Drainage Basin Type

- Exorheic Drainage
- Arheic Region
- Endorheic Drainage
- Endorheic Drainage

Coordinate System: MGA 94 Zone 51

Southern Rangelands Range Condition Change (delta SRC Index) Ts 1998-2002 / Ts 2002-2006

Peter Russell

16 October 2007

Figure 5.17

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

C:\SRCGIS\MapDocuments\WARMS_ChangeInrangeConditionDeltaSRC_Ts98_02to02_06_MGAZ51_20071016.mxd

Region-wide, approximately 80% (of coverage area) shows " Nil or Minor" change in range condition, approximately 15% shows negative change and approximately 5% shows positive change. The reason for this strong pattern is examined by consideration of two region-wide drivers of change that could, either together or singly, produce such a broad change pattern. The two possible drivers of change are:

(i) Multi-year rainfall patterns,

(ii) Regional patterns in herbivore grazing pressure.

(i) Rainfall Patterns

Although the response by vegetation to large episodic rainfall events or to 'good' seasonal rains is usually expressed by rapid recruitment of new plants, sustained positive change in range condition, expressed through changes in soil surface condition and perennial vegetation condition, takes considerably longer. WARMS and the SRC indices derived in this study are designed to detect and monitor these longer-term, multi-year changes rather than the short-term seasonal responses which may fluctuate markedly from season-to-season within an overall trend of stable, improving or declining range condition. For this reason, the examination of the pattern of range condition or, more particularly, the trend from the previous time-slice (Ts1998-2002) to the present, utilises a sequence of rainfall maps beginning in 1996, two years before the change period (ΔTs1998-2002/2002-2006) under consideration. Each map shows aggregate rainfall for two-year periods, classified into percentiles which range from "Extremely low" to "Extremely high" relative to historical records (Figures 5.18 to 5.22). A summary of the rainfall received in the southern rangelands during each two-year period is provided below.

October 1996 – September 1998 (Figure 5.18) During this period, almost the entire northern half to two thirds of the southern rangelands received "Well above average" and "Extremely high" rainfall. The northwest coastal zone from the Ashburton River south to the Gascoyne River received "Average" rainfall as did the Goldfields and Nullarbor regions.

October 1998 – September 2000 (Figure 5.19) In this exceptional period, the entire southern rangelands (indeed, all parts of Western Australia except the far southwest corner) received "Extremely high" rainfall.

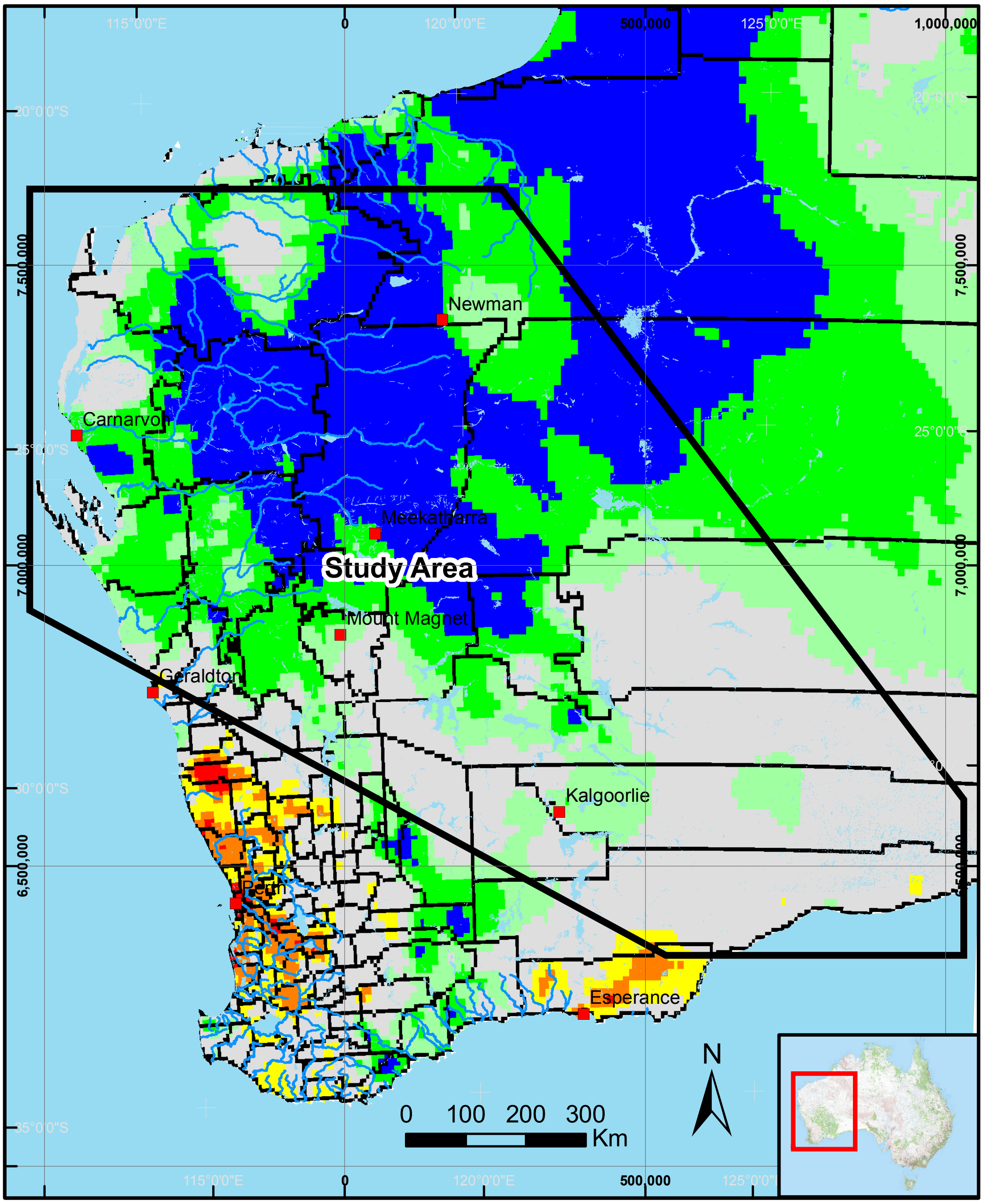
October 2000 – September 2002 (Figure 5.20) Almost all of the southern rangelands received "Average" or more rainfall with the interior receiving "Extremely high" rainfall. The small areas which received "Well below average" or "Extremely low" rainfall were restricted to the coastal zones in the Fortescue River area and south from the Ashburton River.

October 2002 – September 2004 (Figure 5.21) The rainfall pattern during this period is very similar to the previous period. Almost all of the southern rangelands received "Average" rainfall with the interior areas receiving "Well above average" or more rainfall. The only area to receive "Below average" or less rainfall was, again, the coastal Ashburton River area.

October 2004 – September 2006 (Figure 5.22) All areas of the southern rangelands with the exception of the western Nullarbor received "Average" or more rainfall. Large areas of the Ashburton, Gascoyne and Murchison catchments received "Well above average" or more rainfall. The Nullarbor received "Well below average" rainfall during this period.

In summary, almost all of the southern rangelands, for the entire decade from 1996 to 2006, experienced an extraordinary 'run of good years' with average and above average rainfall received in most biennial periods. Exceptions to this pattern of good

Western Australian Rangeland Monitoring System (WARMS)



Legend

Range	(percentile)
Extremely low	(0-10)
Well below average	(10-20)
Below Average	(20-30)
Average	(30-70)
Above average	(70-80)
Well above average	(80-90)
Extremely high	(90-100)

White = Seasonally dry

Source: Bureau of Meteorology

Coordinate System: MGA 94 Zone 51

Southern Rangelands Percentile Rainfall Oct 1996 to Sep 1998 Location of Study Area

Peter Russell

15 October 2007

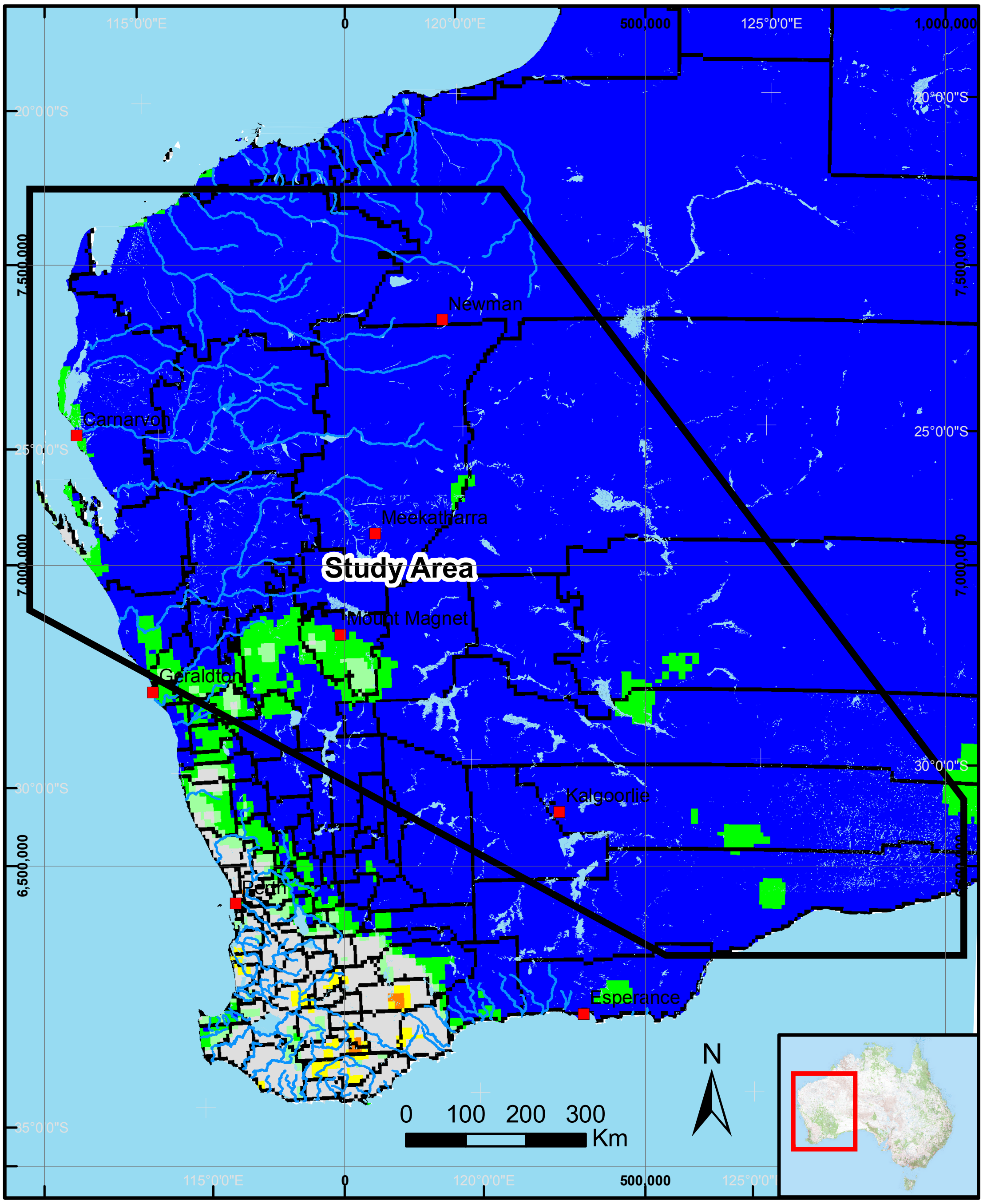
Figure 5.18

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

C:\SRCGIS\MapDocuments\WARMS_WAPercentileRainfallOct1996_Sep1998_MGAZ51_20070911.mxd

Western Australian Rangeland Monitoring System (WARMS)



Legend

Range	(percentile)
Extremely low	(0-10)
Well below average	(10-20)
Below Average	(20-30)
Average	(30-70)
Above average	(70-80)
Well above average	(80-90)
Extremely high	(90-100)

White = Seasonally dry

Source: Bureau of Meteorology

Coordinate System: MGA 94 Zone 51

Southern Rangelands
Percentile Rainfall
Oct 1998 to Sep 2000
Location of Study Area

Peter Russell

15 October 2007

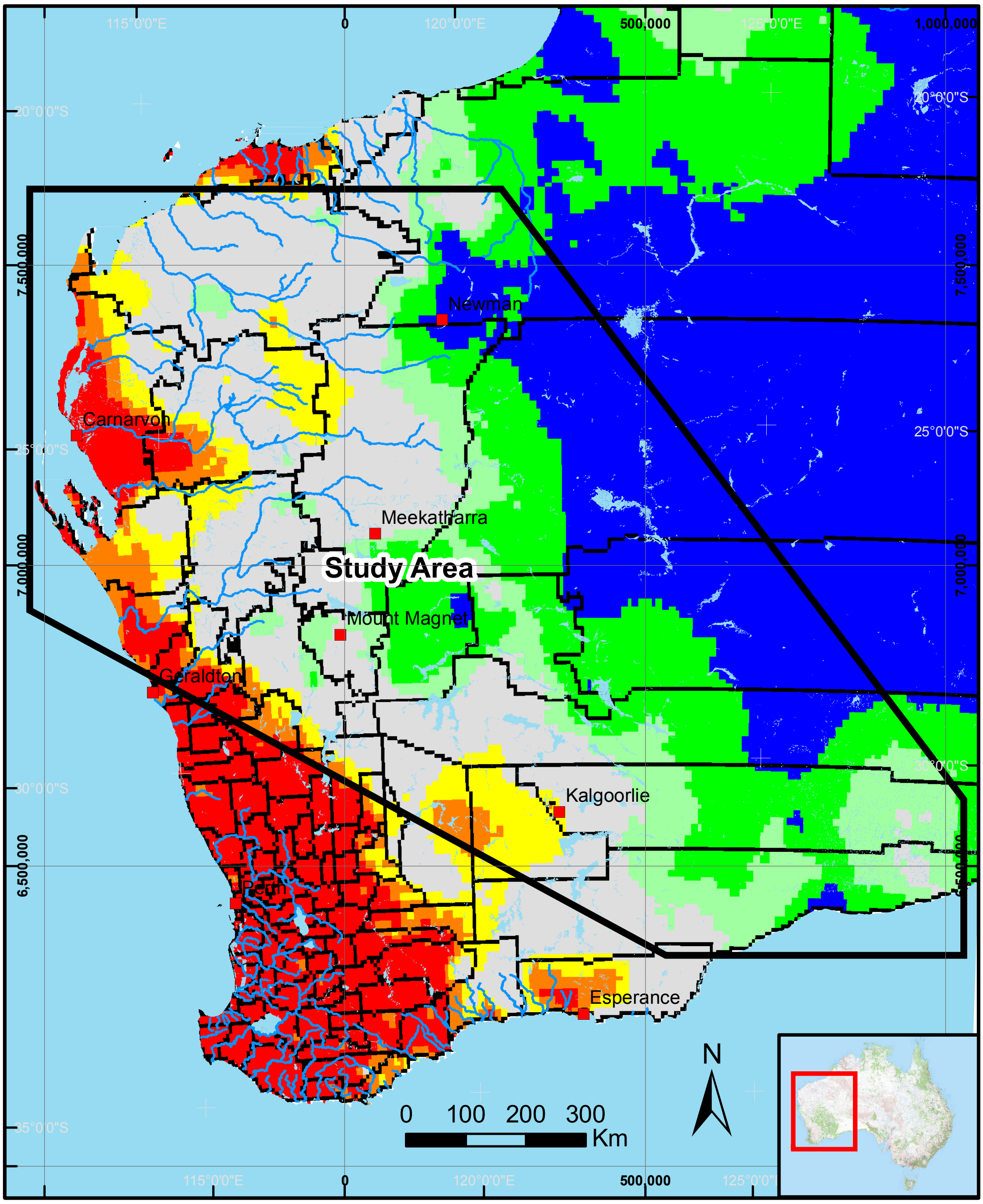
Figure 5.19

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

C:\SRCGIS\MapDocuments\WARMS_WAPercentileRainfallOct1998_Sep2000_MGAZ51_20070911.mxd

Western Australian Rangeland Monitoring System (WARMS)



Legend

Range	(percentile)
Extremely low	(0-10)
Well below average	(10-20)
Below Average	(20-30)
Average	(30-70)
Above average	(70-80)
Well above average	(80-90)
Extremely high	(90-100)

White = Seasonally dry

Source: Bureau of Meteorology

Coordinate System: MGA 94 Zone 51

Southern Rangelands
Percentile Rainfall
Oct 2000 to Sep 2002
Location of Study Area

Peter Russell

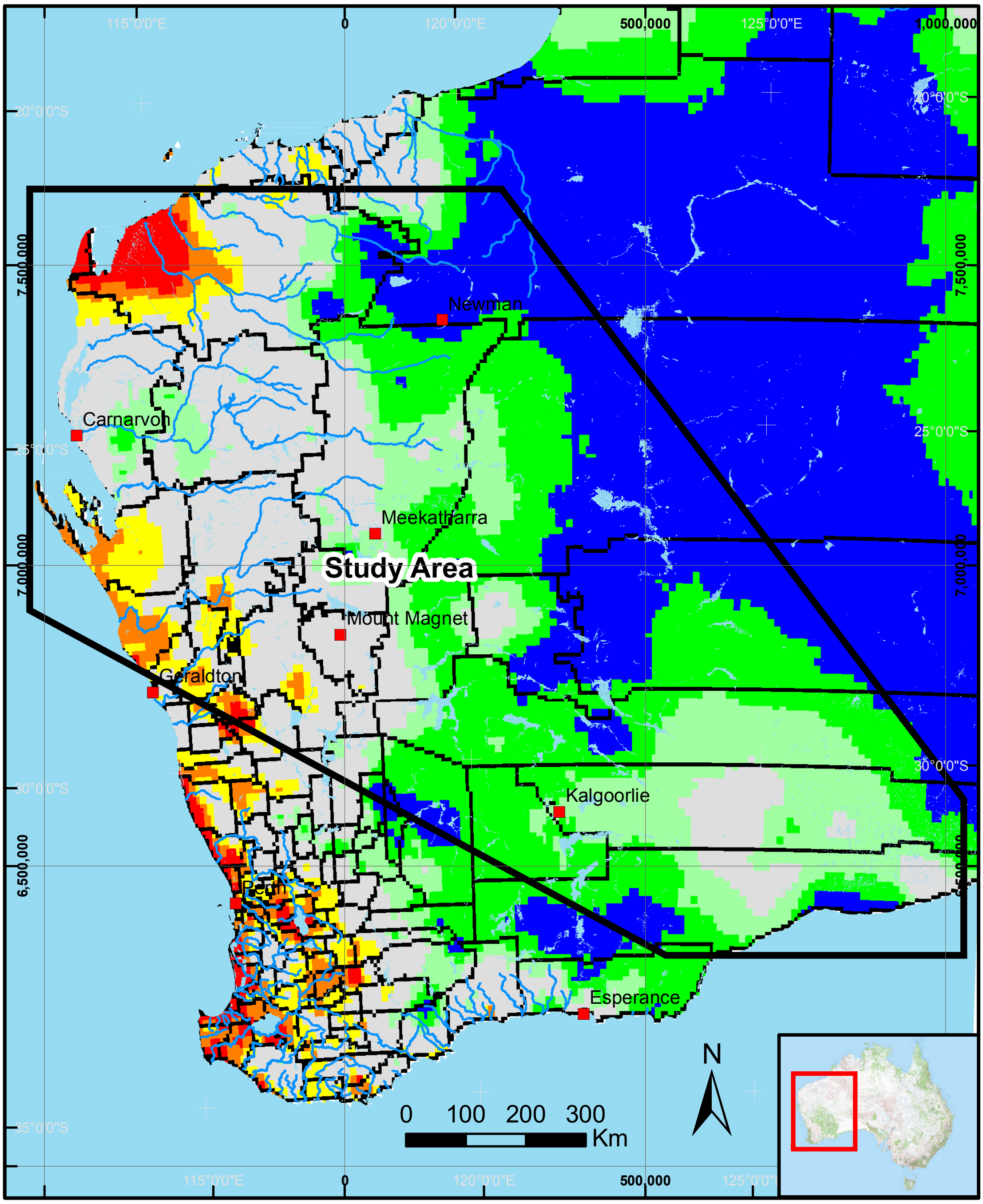
15 October 2007

Figure 5.20

CMAE
CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

C:\SRCGIS\MapDocuments\WARMS_WAPercentileRainfallOct2000_Sep2002_MGAZ51_20070911.mxd

Western Australian Rangeland Monitoring System (WARMS)



Legend

Range	(percentile)
Extremely low	(0-10)
Well below average	(10-20)
Below Average	(20-30)
Average	(30-70)
Above average	(70-80)
Well above average	(80-90)
Extremely high	(90-100)

White = Seasonally dry

Source: Bureau of Meteorology

Coordinate System: MGA 94 Zone 51

Southern Rangelands
Percentile Rainfall
Oct 2002 to Sep 2004
Location of Study Area

Peter Russell

15 October 2007

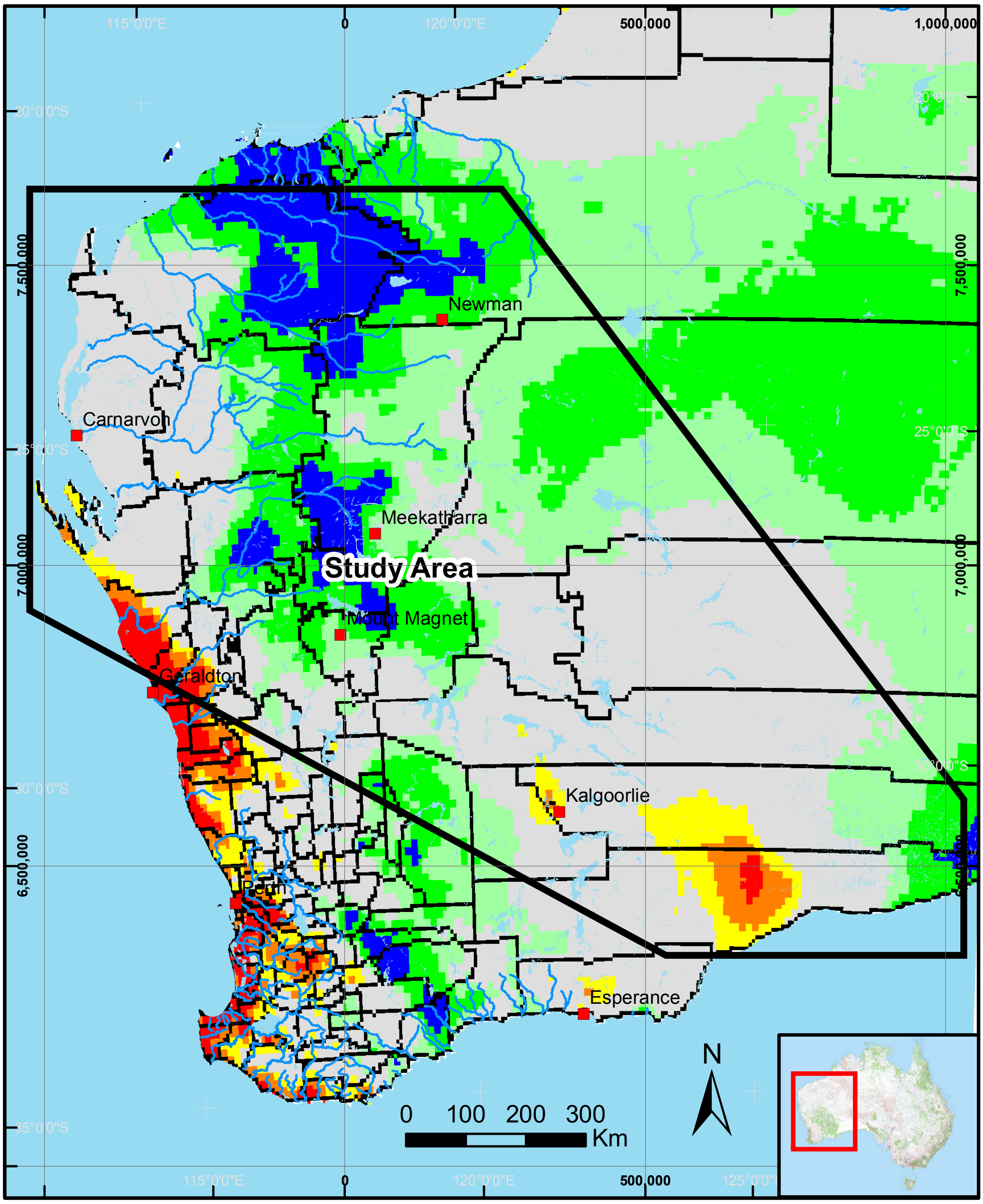
Figure 5.21

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

C:\SRCGIS\MapDocuments\WARMS_WAPercentileRainfallOct2002_Sep2004_MGAZ51_20070911.mxd

Western Australian Rangeland Monitoring System (WARMS)



Legend

Range	(percentile)
Extremely low	(0-10)
Well below average	(10-20)
Below Average	(20-30)
Average	(30-70)
Above average	(70-80)
Well above average	(80-90)
Extremely high	(90-100)

White = Seasonally dry

Source: Bureau of Meteorology

Coordinate System: MGA 94 Zone 51

Southern Rangelands
Percentile Rainfall
Oct 2004 to Sep 2006
Location of Study Area

Peter Russell

15 October 2007

Figure 5.22

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

C:\SRCGIS\MapDocuments\WARMS_WAPercentileRainfallOct2004_Sep2006_MGAZ51_20070911.mxd

rainfall occurred in the early 2000s in the northwest coastal parts and in the mid-2000s on the western Nullarbor.

The very patchy nature of positive range condition change (∆SRC Index) shown in Figure 5.17 for the last change period (∆Ts1998-2000/2000-2006) does not reflect the expected pattern of shrubland-wide improvement which should arise if rainfall alone was the driver of change. Whilst some areas of improvement may have responded to the sequence of 'good' rainfall years, the lack of wide-spread spatial correlation between the patterns of range condition status or change and rainfall strongly suggests that other factors are driving change, in particular negative change. Other factors are considered below.

An additional consideration in relation to rainfall is the region-wide behaviour of rainfall-generated surface water flows. This becomes evident as a pronounced spatial correlation between the pattern of range condition change and drainage type (Figure 5.17). Almost without exception, the catchments showing both the largest area and magnitude of change are of the exorheic type, whilst the endorheic and arheic catchments show, in general, minimal change. This spatial correlation was also noticed for the Landscape Function Factor (LFF) as part of the consideration of range condition status for several time-slices discussed earlier (see Figures 5.10 and 5.14). This strongly suggests that the fundamental relationship between surface water flow dynamics and drainage base levels is expressed by changes in ecological processes and integrity at very large scales. This important insight requires further investigation in the future.

(ii) Grazing Pressure

The other possible driver of region-wide change is grazing by livestock. Whilst definitive site-specific total herbivore grazing pressure data are not available for WARMS sites, very general patterns of livestock numbers are available. Sheep and cattle are the two main types of managed stock in the southern rangelands.

Based on 2004-2005 stock declaration data (Anon. 2006b), a general pattern of stock numbers can be established. Total sheep numbers in the northern parts are in the order of 50,000, gradually increasing to about 1.5 million in the southern parts. Cattle numbers have a contrary geographic distribution. Approximately 10,000 head are in the southern parts, increasing to about 250,000 head in the north. Combining the numbers of each stock type yields an overall geographic pattern. In the north, total stock numbers are in the order of 1.8 million DSE (Dry Sheep Equivalent; 1 cattle unit ≡ 7 DSE) decreasing slightly to about 1.6 million DSE in the south. Since the two parts are of similar area, using stock numbers alone as a surrogate for grazing pressure appears not to explain the pattern of range condition change. The minimal difference in stock numbers is not consistent with the large differential in the magnitude of condition change between the northern and southern parts.

However, when the stock units are expressed as a ratio of actual stock units to potential carrying capacity, then a different picture begins to emerge. Figure 5.23 shows this ratio (as a percentage) for 2005 stock declarations (Anon. 2006b). There is a general reduction in the proportion of stations carrying stock in excess of their carrying capacity from north to south. In other words, the Pilbara and Gascoyne regions have a relatively high proportion of overstocked stations compared to the Murchison, Goldfields and Nullarbor regions. This pattern is consistent with the pattern of range condition change, indicating that grazing pressure may be a driver of regional-scale change. That grazing is a driver of change at local scales is well known and accepted, but its expression at much larger extents is unknown; the work presented here contributes to this insight. The other dimension to herbivory, not considered here, is the contribution by both native and feral (unmanaged) animals, which could be substantial.

Following consideration of shrubland-wide trends, attention is now turned to sub-regional patterns and trends. The area showing the greatest decline in range

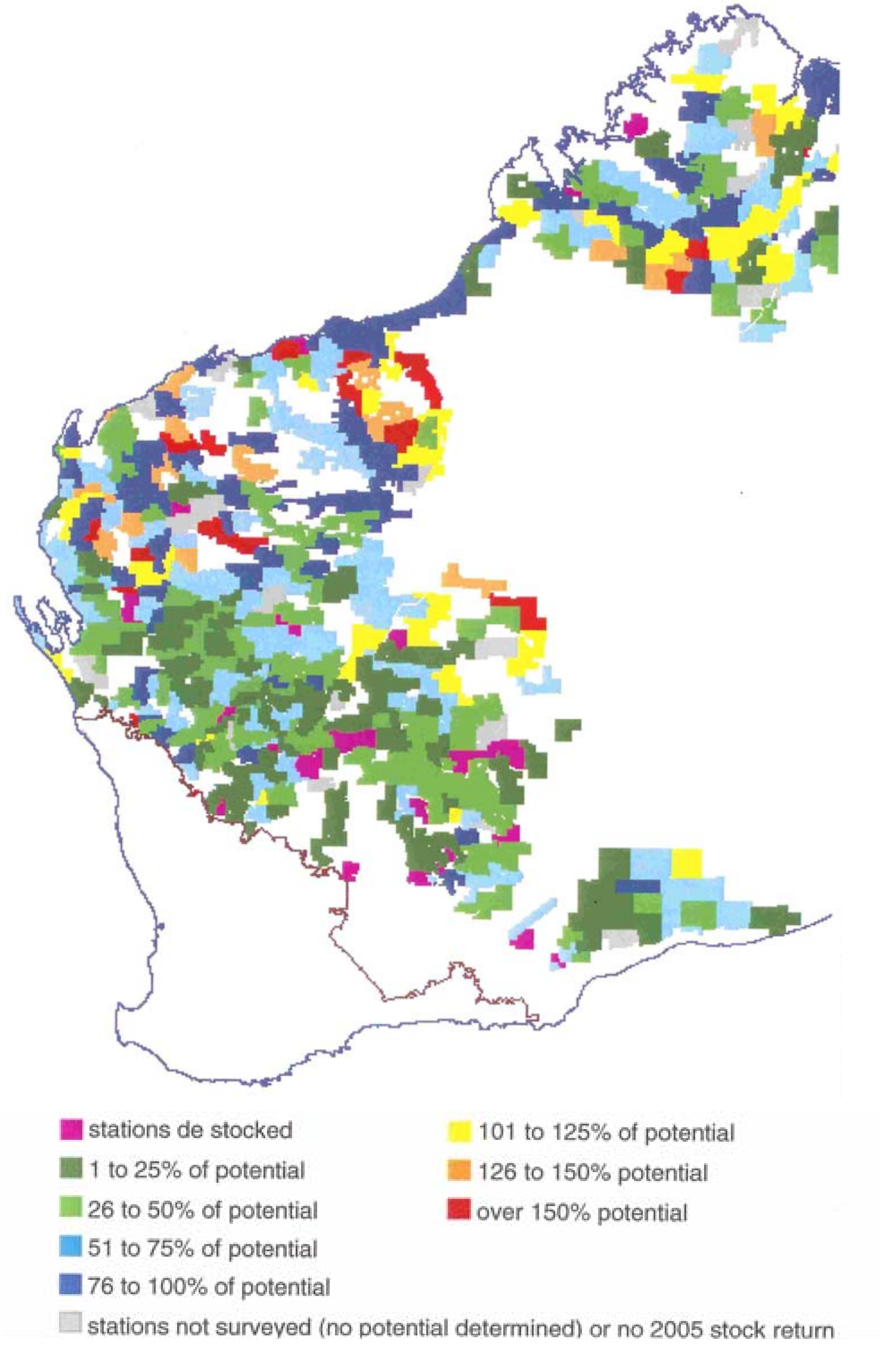


Figure 5.23 Distribution of stocking rate, expressed as the percentage of actual stock units to potential carrying capacity. Based on Annual Livestock Declarations for 2005 **(from WA Annual Pastoral Land Condition Report 2005/2006 (Anon. 2006))**

condition is situated in the lower reaches of the Ashburton River including the Henry River sub-catchment (Figure 5. 17). This area, the largest of five areas in the southern rangelands, has shown a severe decline during two consecutive change periods. Here, a reduction in SRC Index values is driven mainly by a reduction in the values of the LFF and VSF sub-indices with less reduction in the VCF values. This is indicative of accelerated soil erosion, loss of vegetation structural complexity including a reduction in the proportion of mature plants in the vegetation assemblage, and loss of bush clump understorey plants including the berry-bearing plants. The reason for VCF values not showing a commensurate decrease is not clear but it is possible that the number of species (PSR sub-index) and the proportion of palatable decreaser plants (RGR sub-index), which had declined markedly during the previous change period (∆Ts1994-1998/1998-2002), reached a temporary or metastable state during this last change period (∆Ts1998-2002/2002-2006). The underlying cause of change in range condition is suspected to be flood, based on the expected effects on each of the sub-indices.

A second large area of range condition decline is located higher in the Ashburton River catchment in the vicinity of the junction of a major tributary, the Angelo River, and extends to the southwest into the Lyons River subcatchment. Here, the reduction in SRC Index values is mainly driven by a major reduction in LFF values, moderate reduction in VCF values and slight reduction in VSF values. This is indicative of soil degradation and some decline in vegetation compositional complexity, but the underlying causal agent is not clear from this pattern of sub-index changes. This area showed substantial positive change in range condition during the previous change period, ∆Ts1994-1998/1998-2002.

A third area of substantial decline in range condition in the southern Pilbara region is located to the northwest of Newman township, in the upper floodout reaches of the Fortescue River. The reduction in the SRC Index here is driven by substantial reduction in LFF and VSF sub-indices whilst VCF remained little changed. The cause of the change is most likely to be the effect of flood from the heavy July 2005 rains rather than heavy grazing pressure.

The fourth area of range condition decline in the southern Pilbara is situated close to Newman just to the southwest. The decline here, although not as substantial as the three areas described above, is significant for the different underlying cause of change. The reduction in SRC Index values is driven mainly by a reduction in VCF values with minimal reduction in the LFF and VSF sub-indices. This is indicative of loss of some vegetation compositional complexity; soil stability, water/nutrient capture and vegetation structure appear to have not been compromised during this period. The underlying cause in this area is likely to be relatively low (to moderate) herbivore grazing pressure.

In regard to other northern exorheic catchments, areas of moderate decline in range condition occur in the Lyndon and Minilya Rivers floodplain discharge zone into Lake McLeod north of Carnarvon, in the middle reaches of the Wooramel River southeast of Carnarvon and in the Murchison River in several localities.

The area in the vicinity of Lake McLeod has declined in range condition mainly due to the effect of drought, based on the pattern of changes in the SRC sub-indices. This area showed improved range condition during the previous change period.

The reason for the decline in the Wooramel River area is uncertain. Although flood is a possible cause, the decline has occurred through two consecutive change periods.

In regard to the four areas of decline in the Murchison River catchment (Figure 5.17), it appears that all are linked by a similar degradation process. Specifically, the areas are located in the headwaters of the Yalgar River north of Meekatharra, in the headwaters of the Sanford River southwest of Meekatharra, and last, just north of Kalbarri. In each case, the decline in SRC Index values is driven mainly by reduction in LFF values, indicating accelerated soil erosion and some reduction in overall perennial plant density, with varying degrees of effect on vegetation structural (VSF) and compositional complexity (VCF). The area just north of Kalbarri also showed range condition decline in the previous change period with reduced values of LFF (and other sub-indices) noted then as well.

There is a scattering of small areas of range condition decline throughout most of the catchments that will not be examined here. There are, however, a number of areas of range condition improvement located in the Ashburton River, Gascoyne River and Murchison River catchments but, markedly, these are both fewer in number and smaller in area that the areas of decline during this change period (ΔTs1998-2002/2002-2006). The most conspicuous area is located in the upper reaches of the Gascoyne River south of the Waldburg Range, northwest of Meekatharra. The substantial improvement in range condition is driven by a general improvement in vegetation condition, as indicated by the VSF and VCF sub-indices but, surprisingly, the overall increase in the SRC Index is offset by a marked reduction in LFF values, indicative of a reduction in the functional relationship between the soil and vegetation. This apparently paradoxical situation is further confounded by evidence that this area also showed substantial improvement in range condition during the previous change period, strongly driven by improved resource capture and functional relationships between the soil and plants (indicated by increased LFF values). However, what caused the switching of the abiotic-biotic mechanisms leading to the improvement is not clear. Further field investigation is required to resolve this situation. It is likely, however, that the apparently ambiguous aspects are, at least in part, caused by response time-lag effects between changes in soil condition and vegetation, in response to an agent or agents of change.

In considering the endorheic-arheic catchments, the most conspicuous area of change lies approximately midway between Kalgoorlie and Mt Magnet townships, just south of Lake Barlee. The decline in range condition here is driven by a decline in vegetation condition, indicated by modest changes in VSF and VCF index values. Although classified as “Substantial”, the change is, in absolute terms, not nearly as severe as most areas in the southern Pilbara. Importantly, the LFF index, in particular the SSC and PPD sub-indices, remain unchanged during this change period, indicating stable soil surface conditions and no reduction in perennial plant density. The inference from this pattern of change in the indices is that increased herbivore grazing pressure is the primary change agent but it has yet to cause an acceleration of erosion at the monitoring sites. Accelerated erosion could be occurring, however, in the geomorphically active zones not monitored.

Small areas of mostly “Moderate” decline in range condition occur northeast and southeast of Leonora township, and just south of Lake Carnegie. In these areas the decline is driven by changes in the vegetation condition attributes rather than by the soil condition attributes but, importantly, the decline in two of these areas (the Lake Carnegie area and the area northeast of Leonora) has occurred through two consecutive change periods. This is of concern and all such areas in the southern rangelands should be flagged for further field examination to ascertain the cause.

On the positive side, small areas of range condition improvement occur in the arheic Nullarbor region at the northwestern and southwestern extremities (Figure 5.17). The change here is driven by a marked increase in VSF values with some increase in LFF values. Both areas showed a decline in the previous change period.

It is interesting to note that change in range condition in endorheic and arheic drainage basins appears to be mainly expressed by change in vegetation condition whereas in the exorheic catchments, change is expressed by change in soil and vegetation condition, or mainly by change in soil condition. This aspect which appears to apply equally to positive and negative change, is explored further in the next chapter.

5.5 Spatio-statistical Analysis of Range Condition at Time-slice Ts2002-2006

5.5.1 Introduction

For this preliminary analysis, all southern rangeland shrub-type WARMS sites are partitioned into three spatial entities, namely, regions based on the Interim Biogeographic Regionalisation for Australia (IBRA) (Thackway & Cresswell 1995), river catchments/drainage basins, and vegetation assemblages (also known as pasture types). The mean SRC Index for the most recent time-slice, Ts2002-2006, and two measures of dispersion, range and variance, are presented as tables and maps for those spatial entities containing 10 or more WARMS sites.

The main purpose of examining these statistics is that they may help to highlight or reveal underlying systemic or intrinsic ecological characteristics of the spatial entities. However, the reader is reminded that this analysis is based on WARMS sites only, which are ground-based point sources of data for which the reliability of interpretive extrapolation beyond the immediate monitoring site is variable and unknown. Nevertheless, for those spatial entities with a relatively high density of WARMS sites, a higher degree of representativeness of the whole entity is expected and thus some general conclusions or inferences may be made.

5.5.2 Analysis by IBRA Region

In the southern rangelands, WARMS sites occur in 12 IBRA Regions. Seven regions, each containing more than 10 WARMS sites, are listed alphabetically in Table 5.11 below and shown in Figure 5.24.

Table 5.11 Southern rangelands SRC Index statistics (Ts2002-2006) by IBRA Region; n is the number of WARMS sites in each region.

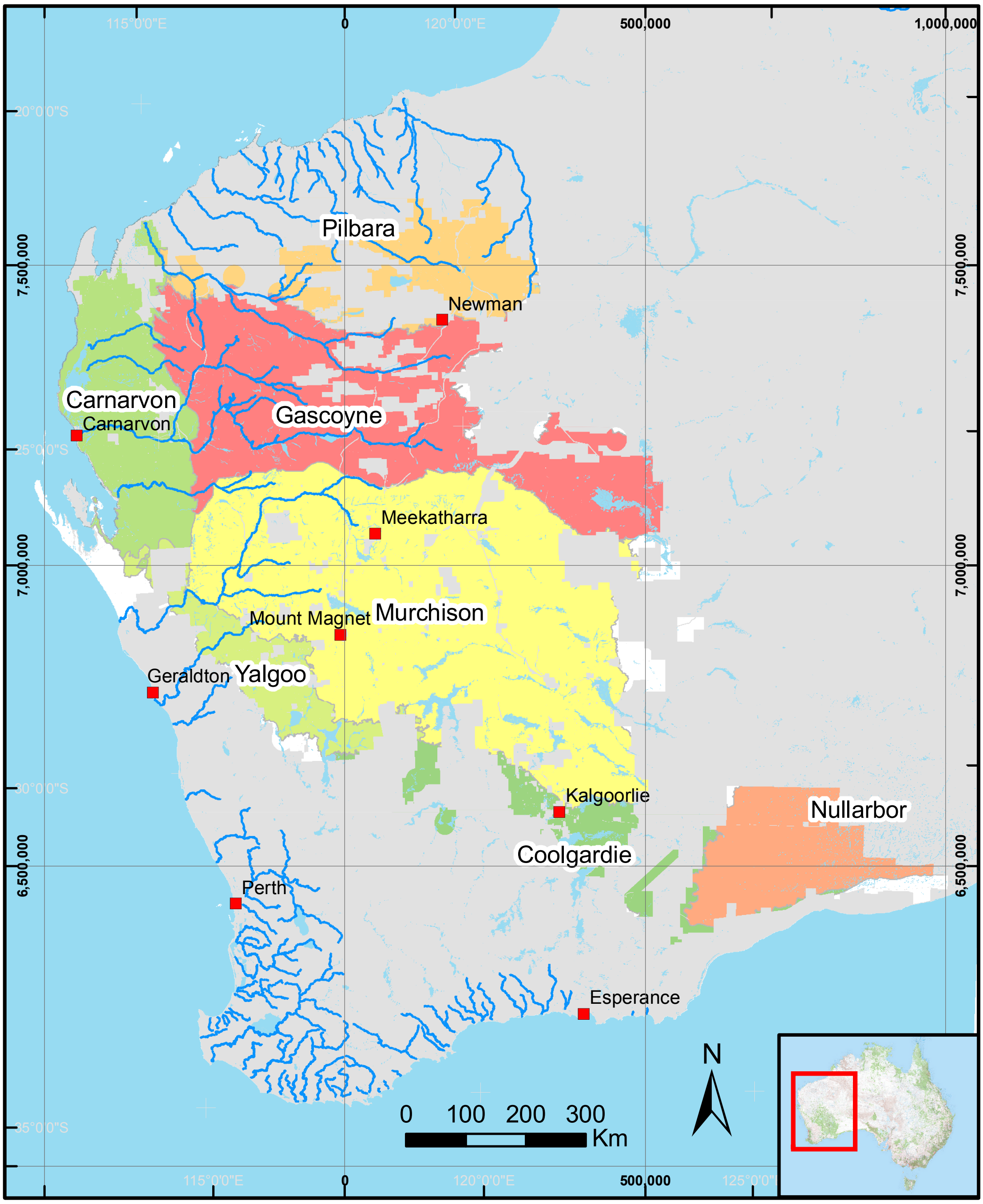
IBRA REGION	*SRC Index*			*Comments*
	Mean (n)	*Min-Max (Range)*	*Variance (s^2)*	
Ts 2002-2006				
Carnarvon	23.7 (18)	19.3-32.0 (12.8)	12.3	
Coolgardie	22.2 (12)	17.3-27.0 (9.7)	8.6	Lowest variance
Gascoyne	26.6 (109)	14.4-74.1 (59.7)	62.9	Highest mean and variance
Murchison	24.6 (280)	13.4-40.5 (27.2)	15.4	
Nullarbor	21.7 (116)	14.1-54.4 (40.3)	41.3	Lowest mean
Pilbara*	23.9 (21)	18.6-32.0(13.4)	17.1	
Yalgoo	23.9 (57)	17.0-37.5 (20.5)	14.3	

* The Pilbara Region is dominated by 'grass-type' WARMS sites; however, only 'shrub-type' sites are included in this analysis.

The mean SRC Index ranges from a low of 21.7 for the Nullarbor Region to a high of 26.6 for the Gascoyne Region. The Gascoyne also has the largest range of SRC Index values, varying between 14.4 and 74.1, reflected in the highest variance (62.9) of all seven regions. The Nullarbor Region follows with a large range of values from a minimum of 14.1 (the second lowest minimum) to a maximum of 54.4 (the second highest maximum behind the Gascoyne), reflected in the second highest variance of 41.2. The lowest variance (8.6) occurs in the Coolgardie Region, although this region has only 12 WARMS sites and thus the statistical comparison with most other regions is much less robust.

The Murchison Region, containing the largest number of WARMS sites (280), has the lowest minimum SRC Index value (13.4) of all regions and a maximum of 40.5, well below the highest maximum (74.1) occurring in the Gascoyne Region, and below the maximum for the Nullarbor Region (54.4).

Western Australian Rangeland Monitoring System (WARMS)



Legend

- Towns
- Lakes and Salt Lakes
- Major Rivers

IBRA SRC Index Variance

- 8.60 - 9.40
- 9.41 - 13.11
- 13.12 - 14.47
- 14.48 - 15.85
- 15.86 - 31.88
- 31.89 - 45.44
- 45.45 - 62.90

Coordinate System: MGA 94 Zone 51

Southern Rangelands SRC Index Variance by IBRA Region At Ts 2002 - 2006

Peter Russell

16 October 2007

Figure 5.24

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

WARMS_RangeCondtionSRCIndexByIbraRegionTS2002_2006_MGAZ51_20071016.mxd

5.5.3 Analysis by River Catchment/Drainage Basin

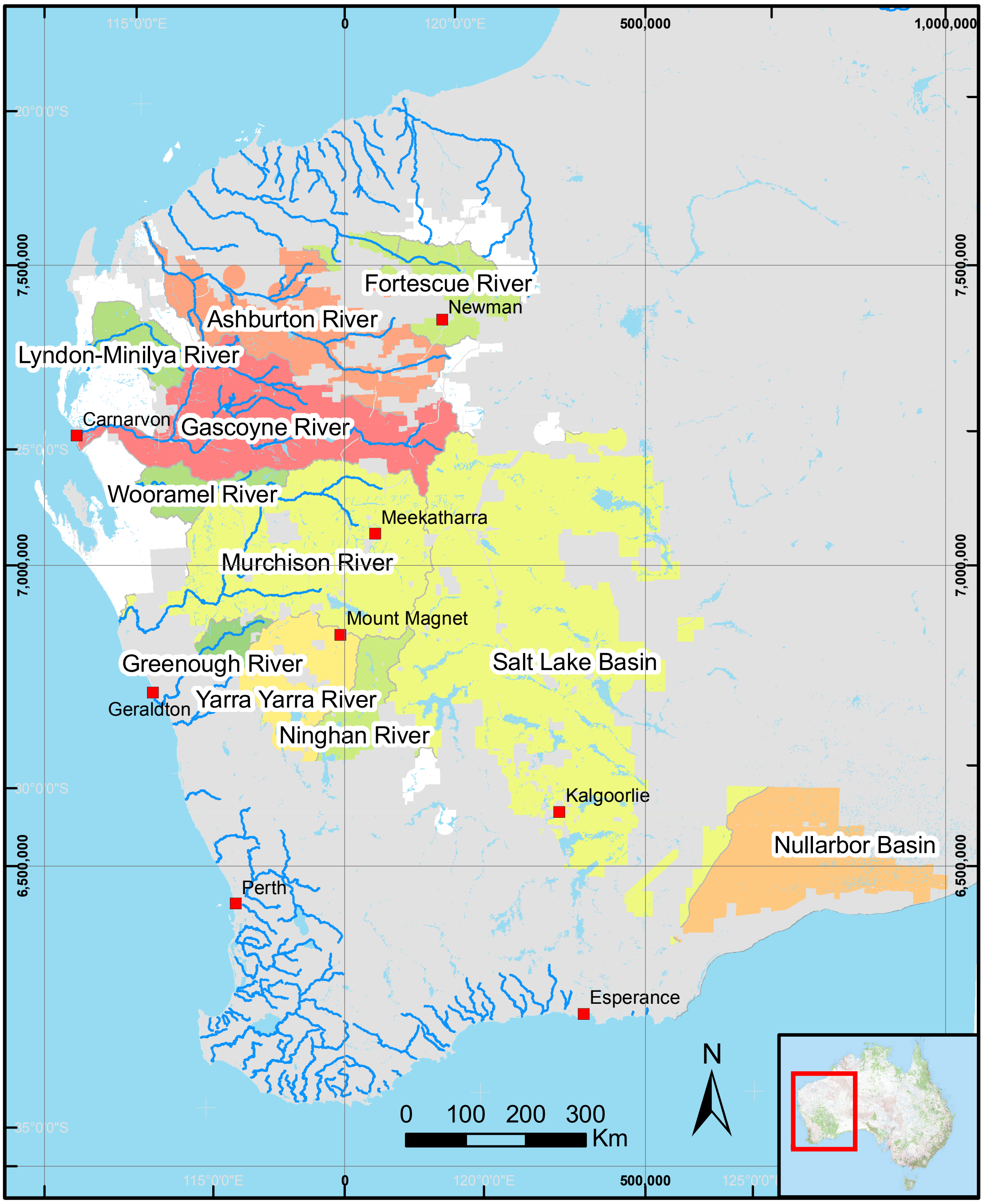
In the southern rangelands, WARMS sites occur in 14 catchments or basins. The 11 catchments which contain 10 or more WARMS sites are listed alphabetically in Table 5.12 below and shown in Figure 5.25.

Table 5.12 Southern rangelands SRC Index statistics (Ts2002-2006) by drainage catchment or basin; n is the number of WARMS sites in each entity.

CATCHMENT or BASIN	***SRC Index***			***Comments***
	Mean (n)	***Min-Max (Range)***	***Variance (s^2)***	
Ts 2002-2006				
Ashburton River	25.2 (28)	14.4-48.0 (33.7)	64.5	High variance
Fortescue River	23.0 (16)	18.6-30.9 (12.3)	12.9	
Gascoyne River	29.3 (35)	17.6-74.1 (56.4)	116.7	Highest mean and variance
Greenough River	24.4 (11)	21.7-28.3 (6.5)	5.7	Lowest variance
Lyndon-Minilya Rivers	23.7 (16)	19.4-32.0 (12.7)	11.3	
Murchison River	24.8 (97)	17.1-39.9 (22.8)	18.2	
Ninghan River	22.4 (32)	13.4-28.8 (15.5)	13.7	
Nullarbor Basin	21.7 (110)	14.1-54.4 (40.3)	42.5	Lowest mean and high variance
Salt Lake Basin	25.1 (203)	15.3-40.5 (25.2)	14.9	
Wooramel River	23.5 (13)	19.2-30.6 (11.3)	11.2	
Yarra Yarra River	24.6 (52)	17.0-46.7 (29.7)	27.6	

Mean SRC Index values vary between 21.7 and 29.3, a range of 7.7. The Gascoyne River catchment sites have both the highest mean SRC Index (29.3) and

Western Australian Rangeland Monitoring System (WARMS)



Legend

- Towns
- Lakes and Salt Lakes
- Major Rivers

SRC Index Variance

- 5.70 - 7.43
- 7.44 - 11.30
- 11.31 - 13.70
- 13.71 - 21.77
- 21.78 - 33.00
- 33.01 - 49.64
- 49.65 - 74.35
- 74.36 - 116.70

Coordinate System: MGA 94 Zone 51

Southern Rangelands SRC Index Variance by Catchment At Ts 2002 - 2006

Peter Russell

16 October 2007

Figure 5.25

CMAE

CENTRE FOR THE MANAGEMENT OF ARID ENVIRONMENTS

WARMS_RangeCondtionSRCIndexByCatchmentTS2002_2006_MGAZ51_20071016.mxd highest maximum value (74.1) in contrast to the Nullarbor Basin sites which have the lowest mean (21.7) and second lowest minimum value (14.1). With the exception of sites in the Gascoyne River catchment, all other catchments have mean SRC Index values of less than 25.3.

The Gascoyne River catchment also has sites with the largest range of SRC Index values (17.6-74.1), reflected in the highest variance (s^2=116.7) of all catchments. The Nullarbor Basin has sites with the second largest range of SRC Index values (14.1-54.4), again reflected in a high variance (s^2=42.5), in turn followed by sites in the Ashburton River catchment with a range of values from 14.4 to 48.0 (33.7) and very high variance (s^2=64.5). All other catchments have sites with much lower variances (s^2<30); of note in this low variance group are the sites in the Murchison River catchment and the Salt Lake Basin which have variances (s^2) of 18.2 and 14.9 respectively, both less than their respective mean SRC Index values.

5.5.4 Analysis by Vegetation Assemblage

In the southern rangelands, WARMS sites occur in at least 17 vegetation assemblages or pasture types. Table 5.13 below lists alphabetically, the 12 vegetation assemblages which contain 10 or more WARMS sites for the latest time-slice Ts2002-2006. A map of the vegetation assemblages is not included.

Table 5.13 Southern rangelands SRC Index statistics (Ts2002-2006) by vegetation assemblage; n is the number of WARMS sites in each assemblage.

VEGETATION ASSEMBLAGE	***SRC Index***			***Comments***
	Mean (n)	***Min-Max (Range)***	***Variance (s^2)***	
Ts 2002-2006				
Bladder saltbush	20.7 (59)	15.6-37.4 (10.0)	13.4	Lowest mean
Hardpan mulga shrub	25.7 (163)	17.9-39.2 (21.4)	14.6	
Mixed halophytic	24.1 (99)	17.9-46.7 (28.8)	14.4	
Other	25.0 (14)	21.3-34.6 (13.3)	10.6	Lowest variance
Pearl bluebush	23.1 (69)	14.1-54.4 (40.3)	61.9	High variance
Sago bush	21.4 (57)	13.4-29.9 (16.5)	13.3	
Sandplain Acacia shrub	23.5 (11)	19.1-29.6 (10.5)	12.4	
Sandy granite Acacia shrub	26.5 (20)	21.8-37.5 (15.6)	14.8	
Silver saltbush	27.1 (16)	14.4-48.0 (33.7)	82.3	Highest mean and variance
Stony Acacia-Senna-Eremophila-Cottonbush	25.2 (41)	17.6-53.0 (35.4)	30.0	
Stony mixed chenopod	25.6 (26)	19.0-43.5 (24.5)	36.0	
Wandarrie grass	24.0 (27)	19.0-40.5 (21.6)	18.2	

The Silver saltbush vegetation assemblage contains sites with the highest mean SRC Index value (27.1), whilst Bladder saltbush hosts sites with the lowest mean value (20.7); this is a range of 5.7 which is slightly larger than the range shown by sites partitioned by IBRA Regions (4.9) and less than the sites partitioned by catchment/basin (7.7).

The largest range of SRC Index values is shown by sites in the Pearl bluebush assemblage (40.3) followed closely by sites in the stony Acacia-Senna-Eremophila-Cottonbush (35.4), Silver saltbush (33.7) and mixed halophytic (28.8) assemblages.

Bladder saltbush assemblage contains sites showing the smallest range of SRC Index values (10.0).

The highest variance is shown by sites within the Silver saltbush (s^2=82.4) and Pearl bluebush (s^2=61.9) assemblages, both considerably larger than their mean SRC Index values. Apart from 'Other', the assemblages with sites showing very low variance are Sandplain Acacia shrub (s^2=12.4), Sago bush (s^2=13.3) and Bladder saltbush (s^2=13.4), with the mixed halophytic (s^2=14.4), hardpan mulga shrub (s^2=14.6) and sandplain granite Acacia shrub (s^2=14.8) assemblages containing sites with only slightly greater variance.

5.6 Summary

The work presented in this chapter is founded on a hierarchical suite of indices encompassing the three principal components of site-scale ecosystem integrity namely, structure, function and composition. The indices were derived from soil and vegetation metrics captured from WARMS transects over the last 16 years. This section summarises, for each time-slice, the key observations of spatial and temporal patterns and changes in the ecological integrity or range condition of the southern rangelands of Western Australia.

Table 5.14 below summarises the proportion of sites in each class of range condition for each time-slice. The reader is cautioned, however, that only very general and potentially misleading inferences can be made from the data in this table. For example, the table provides no indication of the proportion of sites which remain in the same condition class and those which change class between time-slices. In an extreme situation, it would be possible to have a complete turnover of sites from one class to another between time-slices but to end up with unchanged proportions of sites in each class. In other words, this data provides no information on the spatial distribution of sites in good or degraded condition, and the change dynamics through time. Better appreciation of range condition is gained by examining the maps.

Table 5.14 SRC Index - percentage of WARMS sites in each range condition class for each time-slice, for the southern rangelands.

Time-slice (Ts)	***"Very Poor" (%)***	***"Poor" (%)***	***"Fair" (%)***	***"Good" (%)***	***"Very Good" (%)***
Ts1990-1994	1.8	23.2	53.6	16.1	5.4
Ts1994-1998	1.2	32.6	49.3	14.6	2.3
Ts1998-2002	1.5	22.0	55.0	15.4	6.1
Ts2002-2006	2.2	26.6	53.3	13.0	5.0

In the first time-slice examined, *Ts1990-1994*, reduced range condition was frequently expressed by low Landscape Function Factor (LFF) and Vegetation Structure Factor (VSF) values. No region-wide spatial pattern in any of the indices could be ascertained due to the very limited sites coverage.

In the second time-slice, *Ts1994-1998*, for which there is much better coverage, approximately 49% of sites were in "Fair" condition, 34% in less than fair condition and only 17% in better than fair condition. Whilst there was no region-wide spatial pattern exhibited by the SRC Index, the LFF sub-index did show a pattern of generally increasing values across the southern rangelands from northwest to southeast. The coverage of sites common to this and the previous time-slice is too limited to be able to draw clear temporal trends in range condition. Nevertheless, the principal area of decline, during this change period, is located in the lower-upper reaches of the Gascoyne River. The adverse change was attributed to high grazing pressure, reflected in changes to the vegetation and soil condition attributes.

For the third time-slice, *Ts1998-2002*, there is good coverage of sites. Approximately 55% of sites were in “Fair” condition, 24% in worse than fair condition and 21% in better than fair condition.

There is only a weakly expressed spatial pattern of decreasing range condition across the southern rangelands from northwest to southeast; however, the LFF, VSF and VCF sub-indices show stronger spatial trends at this time. LFF exhibits an increase in values from west to east, whilst VSF and VCF show a divergent spatial pattern of decreasing values from northwest to southeast, mirroring the weak SRC Index pattern.

In regard to temporal change from the previous time-slice, there is a clear spatial pattern of declining areal extent and magnitude of change in range condition from north to south across the southern rangelands. The area showing the greatest decline is situated in the Ashburton River catchment, and contrasts with other areas in the southern Pilbara region which show widespread improvement during this change period. Decline in range condition is usually reflected in reduced values of the three principal sub-indices LFF, VSF and VCF. In most cases, high grazing pressure was inferred to be the prime causal agent of adverse change. In contrast, areas of improvement were mainly driven by marked increases in LFF values, reflecting better water and nutrient capture and reduced erosion.

In the fourth and last time-slice, *Ts2002-2006,* approximately 53% of sites are in “Fair” condition, 29% in worse than fair condition and 18% in better than fair condition. Again, a pronounced shrubland-wide pattern of range condition is not present but more localised or intra-regional trends are evident. For example, condition appears to decrease from the southwestern parts of the Nullarbor to the northern and eastern parts.

Importantly, however, the Landscape Function Factor (LFF) does show a pronounced pattern, clearly differentiating sites across the shrubland into two groups. In general, sites with higher LFF values occur within endorheic-arheic type catchments in contrast to sites with lower LFF values in exorheic catchments. A similar although less distinct pattern was revealed in the previous time-slice.

In terms of change in range condition, there is a clear shrubland-wide trend of decreasing change, in both area affected and magnitude, from northwest to southeast. This trend was also observed for the previous change period. The examination of rainfall and grazing pressure, as the most likely drivers of region-wide range condition change, concluded that stocking rate, expressed as a proportion of potential carrying capacity, had a greater overall effect on the pattern or trend of change than did rainfall. Areas of improvement were generally more limited in extent than areas of decline, during the decade of good rains.

As was found for previous change periods, the area of greatest decline occurred in the Ashburton River catchment. Here, the decline was driven by marked reduction in LFF values, usually accompanied by reductions in one or both vegetation sub-indices. Accelerated soil erosion is widely implicated in the Ashburton, other northern catchments and in the Murchison River catchment.

In addition to the above observations, examination of changes in range condition at local scales in this and earlier change periods revealed a small number of cases of apparently paradoxical behaviour/responses by the SRC indices. The upper reaches of the Gascoyne River, just south of Waldburg Range, is an example. Here range condition improvement, indicated by increased SRC Index values driven by increased VSF and VCF values, is offset by very low values of LFF. This situation, although not resolved, highlights the likely confounding role of response time-lag and feedback links between changes in soil condition and vegetation.

The spatio-statistical analysis by IBRA region and drainage catchment confirms the pattern of regional characteristics determined above. In both analyses, the Gascoyne (by IBRA and catchment) has the highest mean range condition (SRC Index) but also has the highest variance. This is consistent with the very heterogeneous pattern of areas in very poor and very good condition. The Nullarbor also has a mix of sites in heterogeneous condition and overall is the region with the poorest range condition.

6 Synthesis

Chapter 6: SYNTHESIS, CONCLUSIONS and RECOMMENDATIONS

6.1 Introduction

The work reported here has advanced the conversion of WARMS monitoring data into information. Watson (1997, pp.8-49) emphasised the fundamental necessity of undertaking repeated measurements in order to detect change. Whilst also recognising the very considerable difficulty of establishing the relationship between causes and observed or detected change, he strongly urged those involved in rangelands monitoring, particularly in Western Australia but elsewhere as well, to tackle "the greater challenge of turning range monitoring output from data through information and knowledge to wisdom and action". This work has achieved part of Watson's vision.

WARMS is an established monitoring system with a consistent, robust data capture protocol and by late 2006, all sites in the southern rangelands had been re-assessed at least once and most at least twice. This maturity is evidenced by Watson *et al.* (2007) being able to provide a statistical analysis of vegetation change for the entire southern rangelands for the first time in the history of WARMS.

Several key features differentiate the work presented here from previous comprehensive analyses of WARMS data (Duckett, Holm & Thomas 1996; Watson, Thomas & Fletcher 2007). First, attributes related to perennial vegetation and landscape function, including soil surface condition, are included. Second, this the first study to develop a single integrated numerical index of ecological integrity or range condition for the shrublands of Western Australia, and third, range condition and change through time are presented as maps. This has enabled the distribution of range condition to be examined for the whole of the southern rangelands, and to discern previously unknown spatial and temporal patterns.

The incorporation of landscape function builds on the doctoral work by Holm (2000) who demonstrated for the shrublands, a general relationship between the movement and accumulation of resources, vital for plant growth, and phytomass productivity. Dysfunctional or degraded landscapes produce less phytomass compared to functional, non-degraded landscapes. The hydrogeomorphic and biogeochemical processes involved in the redistribution, capture and cycling of water and nutrients operate at multiple spatial and temporal scales, from vegetated patch to catchment.

6.2 Synthesis

The pattern of range condition and change elucidated in this study is essentially a data-driven model. Whilst the concept of ecological integrity for range condition has been utilised, no one ecological model has been used. Instead, elements of several ecological models (outlined in Chapter 2) relating to key environmental responses, either explicitly or implicitly, have been integrated into the development of a hierarchical framework and overall index of ecological integrity (Chapter 4). There is also an element of a statistical model through examination of the degree of correlation between the indices representing responses to disturbance processes (Chapter 4).

For this study, the data had already been collected. Thus, the overall approach has been to fit the available WARMS data into a pragmatic data-ecological model and then to test statistical relationships. This is contrary to the more usual approach of a model driving the collection of specific data with known or tested relationships.

Generalised shrubland-wide patterns of range condition or ecological integrity at WARMS sites, based on the Shrubland Range Condition (SRC) Index and its sub-indices, are shown diagrammatically in Figure 6.1. Generalised patterns of range condition change are shown in Figure 6.2 and are discussed a few pages below.

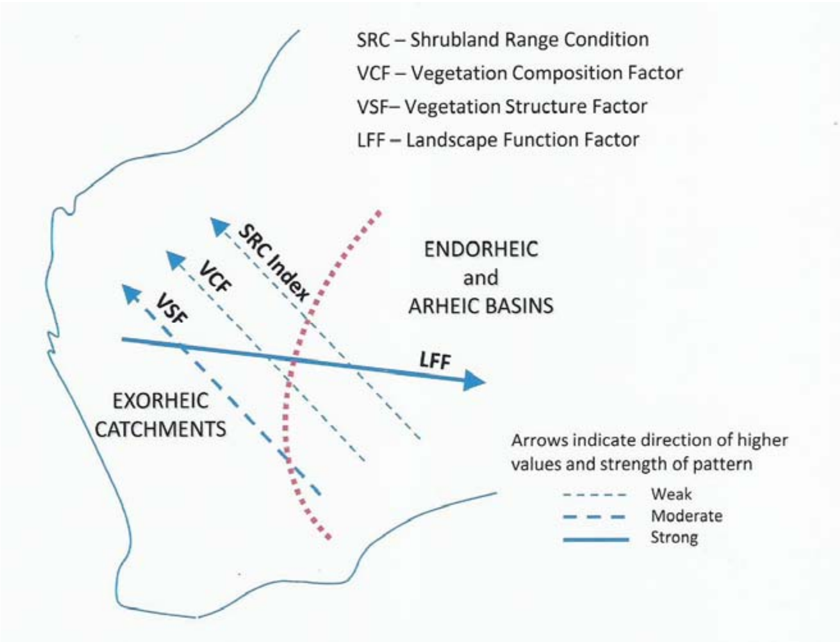


Figure 6.1 Schematic Map Showing Regional Patterns of SRC Index and Sub-Index Values Across the Southern Rangelands of WA

There are a number of shrubland-wide patterns and indexical relationships evident in the maps presented in the previous Chapter. These are synthesised here and an explanation provided. First, there is a weak pattern of generally higher SRC Index values occurring in the northern parts compared to the southern parts for most of the time-slices. However, the overall pattern is confounded in some areas such as the northwest coastal zone which show anomalously low values at times. The Nullarbor is distinctive as a region containing a higher proportion of sites with lower SRC Index values. However, the northern areas show the greatest variation with a significant number of sites with low SRC values and others with high values, reflecting a pattern of decreasing variation across the Gascoyne - Murchison - Goldfields regions.

Second, the weak shrubland-wide pattern of decreasing range condition from northwest to southeast is mirrored by a similarly weak pattern of vegetation composition (VCF) values and a moderately strong pattern of vegetation structure values (VSF). This is indicative of generally declining structural complexity north to south, particularly reflecting the reduced presence of understorey bush clumps and numbers of berry-bearing plants. The compositional pattern reflects generally higher species richness in the northern parts compared to the southern parts, particularly the depauperate Nullarbor. However, the Landscape Function Factor (LFF) shows a distinctive contrary pattern of values generally increasing from west to east across the shrublands. This divergent or contra-spatial pattern, explains, at least in part, the low statistical correlation between the SRC Index and LFF noted in Chapter 4.

Third, in the northern parts, it was found that the SRC Index values are driven by either (a) all three principal sub-indices (LFF, VCF and VSF) behaving sympathetically or in concert, or (b) the LFF index showing strong contra-behaviour to the VCF and VSF indices. For example, a moderate SRC Index value at a particular site may be driven by moderate vegetation index values but offset by a very low LFF value. In a few cases, one of the vegetation indices displayed contra-behaviour to the other indices. The site-specific indexical behaviour outlined here was also generally observed for clusters of sites showing a similar range condition status. This strongly suggests a systemic biophysical explanation for the different behaviours, rather than site-specific characteristics or even field data error.

Fourth, in the southern and eastern parts, particularly in the Nullarbor region, indexical behaviour was different again. Here, relatively low SRC Index values were generally driven by relatively low vegetation index (VCF and VSF) values but not by correspondingly low LFF values. In general, the eastern and southern parts, particularly the Nullarbor, have higher LFF values compared to the northwestern parts of the shrublands.

Based on the four patterns noted above, the indexical behaviour appears to be complicated and/or inconsistent. However, it is proposed that two biophysical explanations may account for at least some of the behaviour and relationships; they are:

(a) Biogeochemical and/or hydrogeomorphic process time-lag effects, and

(b) Drainage catchment characteristics.

The multi-factorial biogeochemical and hydrogeomorphic processes occurring in the landscape operate at different rates. Therefore, there are likely to be differences in the response rate of vegetation and soil to any particular disturbance or agent of change. At any point in time, there may be a lag between vegetation and soil surface condition, in response to change, reflected in contra-behaviour of the SRC Index sub-indices. For example, in a degradation scenario of rapid and severe defoliation of plants by a high rate of herbivory, the effect will be strongly and quickly reflected by reduced values of the vegetation indices (VCF and VSF) but not necessarily by the Landscape Function Factor (LFF); significant change in LFF values will occur in response to the reduced vegetation integrity but the response may only be triggered or activated by subsequent rainfall (or wind) episodes.

Other degradation scenarios or indeed recovery situations are likely to have different lag characteristics. At many sites, LFF appears to change ahead of the vegetation indices; accelerated erosion here would trigger a response or change in the vegetation indices in due course.

It appears from an examination of the indices, site-by-site through time, a lag continuum exists, ranging from concurrent response in the vegetation and landscape function indices through to disparate lagged response, with either the vegetation or the landscape function leading the response. The reasons for this stepped response or apparent change between equilibrium and disequilibrium states are likely to be complex, relating to the nature of the disturbance, vegetation and soil characteristics, local patterns of rainfall and process feedback loops.

The second proposed explanation for the indexical behaviour is related to drainage catchment type. The pattern of LFF values shows a distinct differentiation of WARMS sites into two main groups. In general, sites located within exorheic catchments have lower values compared to sites located within endorheic and arheic basins. The explanation is tied to catchment base-levels. For exorheic catchments in the southern rangelands, the ultimate base-level is the Indian Ocean (sea level). For these catchments, in general, the topographic gradient between headwaters and the coast, and between intermediate or temporary base-levels, is considerably steeper than for the endorheic catchments which drain into the topographically flat palaeodrainage salt lake system of the interior. Because of greater topographic relief and gradients, rates of erosional incision in exorheic catchments are expected to be considerably higher than in endorheic catchments. Erosion rates in arheic areas such as the Nullarbor karst plain and the large interior sand plains are very low because of the general paucity of sustained and concentrated surface water flows. Other factors such as rainfall amount, intensity and volume of run-off come into play, however, the LFF index appears to synthesise the collective effect of all factors over time.

Whilst differences in the behaviour of surface water flow in different catchments are expected based on theoretical considerations, this study provides strong region-wide empirical evidence of the fundamental relationship between catchment type and its intrinsic erosional regime. This finding provides support to the field observations and photographic evidence of erosional processes involved in landscape incision and lateral cutback described by Tinley and Pringle in several publications and unpublished material (Tinley 1977; Pringle & Tinley 2003; Pringle & Coleman 2006; Pringle, Watson & Tinley 2006).

Change patterns

The above discussion has focused on the status or state of the patterns of range condition and contributing factors.

The patterns of change in range condition also reveal some region-wide insights and generally reinforce the conclusions derived earlier. Figure 6.2 diagrammatically summarises the shrubland-wide patterns of change in range condition.

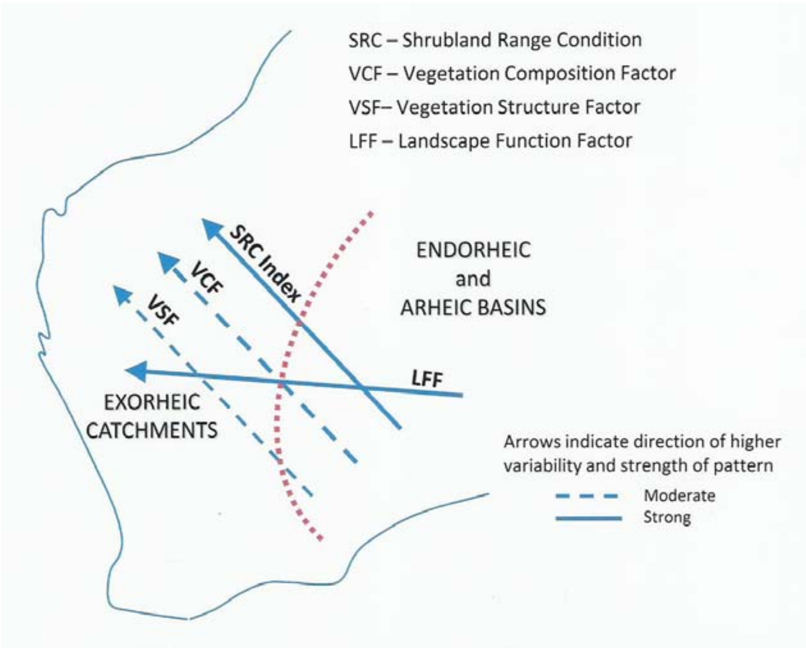


Figure 6.2 Schematic Map Showing Regional Patterns of Variability of SRC Index and Sub-Index Values Across the Southern Rangelands of WA

Examination of change in range condition (SRC Index) reveals a strong geographic-temporal pattern (see Figures 5.8, 5.12, 5.17 in Chapter 5).

The northern parts of the shrublands consistently show the greatest change through time in both the areal extent (site clusters, number of sites undergoing change), and degree of change compared to the southern parts. There is a clear northwest to southeast trend of declining change from the Ashburton and Gascoyne regions, through the Murchison and into the Goldfields, where there has been minimal change in range condition over the last two decades. The Nullarbor shows slightly more change than the Goldfields region, and this change, principally in the western parts, has been an improvement.

The minor positive change in condition of sites in the western Nullarbor and the generally minimal change for most of the Goldfields sites, contrasts markedly with the northern catchments. Here, there are large clusters of sites in the Ashburton and Gascoyne regions which have shown continuing decline in condition since the mid-1990s. The only exception to this sad story is at sites in the upper reaches of the Gascoyne catchment where there has been almost continual improvement since the mid-1990s.

The Murchison catchment shows a mixed pattern – some sites have fluctuated in condition over the last decade or so – but there are two clusters of sites which have shown continual decline over this period.

In most cases of adverse change in the northern region, a high rate of herbivory is postulated as the cause. At a few sites, flood was determined to be the primary agent.

In regard to the differentiation of sites in exorheic or endorheic-arheic catchments, based on absolute values of LFF discussed earlier, the degree of change in LFF values also provides a similar differentiation. In this case, sites located in endorheic-arheic catchments display minimal change through time, again reflecting relatively stable landscape function, particularly soil surface condition. At the sites where change in range condition has occurred, change is usually driven by change in the vegetation structural and compositional complexity.

In contrast to the endorheic-arheic sites, sites located in the exorheic catchments where change has occurred frequently display maximal changes in LFF through time. Here, changes in range condition are usually driven by changes in LFF, VCF and VSF values, indicating overall broad based spectrum changes in ecological integrity, or in several cases, principally by LFF.

Overall, for the entire southern rangelands, since 1994, there has been a very slight net increase in the number of sites that have improved in range condition. However, this generalisation disguises the legacy of historical degradation and ongoing poor livestock management (overgrazing) that is hindering the widespread recovery in range condition, despite more than a decade-long sequence of above-average rainfall in most areas except the coastal zone south from Carnarvon.

6.3 Conclusions

The principal conclusions arising from this study are:

(a) WARMS sites are able to capture changes in vegetation and soil surface condition.

(b) Change in range or ecological condition was neither uniform nor random.

(c) Where adverse change is detected by WARMS sites or more importantly by clusters of sites showing similar change, the area should be flagged for prompt follow-up field investigation to determine the cause(s) of change; change is likely to be more advanced in the more active parts of the landscape. Attention is required in parts of the Ashburton, Gascoyne and Murchison catchments.

(d) There was low spatial and temporal correlation between the regional syntheses of rainfall and the pattern of range condition and range condition change. It is concluded that either (i) that the pattern of change reflects, in part, the effect (adverse or beneficial) of local storm events, or (ii) more likely, the effects of over-grazing generally subsume the effects of rainfall. This effect was more noticeable in the northern parts of the southern rangelands. In this regard, as suggested by Sharp and Bowman (2004), the detection of recruitment events needs further investigation to differentiate between region-wide climatic conditions and local, site-specific management effects.

(e) The pattern of Landscape Function Factor (LFF) values and their pattern of change through time provide clear regional characterisation of endorheic-arheic and exorheic catchment types. Careful and ecologically benign land management of the more active exorheic catchments needs to be practiced to minimise soil erosion.

6.4 Recommendations

Whilst the research work described in this thesis is a milestone in the mapping and analysis of rangeland ecological health or condition in Western Australia, it should not be seen as an endpoint. Rather, it is a platform or stage from which further necessary work can proceed.

Good rangeland management and conservation programmes need to be informed by sound strategic monitoring programmes embedded in a management framework. The imperative for monitoring is now greater than ever due to accelerated climate change and intensification of land use. This author envisages an enhanced role for WARMS as part of a greatly enhanced system to monitor and inform ecological integrity assessments and biodiversity conservation programmes over the whole of the rangelands, not just for the pastoral areas but also for the conservation estate and other land uses. Clearly, this is an enormous task that would require the participation of multiple government agencies and community under the direction of the RCG (Rangeland Coordination Group).

Such a monitoring system would need to provide information at a range of spatial and temporal scales for the major components of ecological integrity (function, structure and composition) at several levels of biodiversity organisation. The major research challenge is to decide which questions need to be answered and therefore which attributes to use at each level of organisation. Whilst much of this work has already been done over the last decade or more (Anon. 2001; Whitehead *et al.* 2001), the challenge remains to put this information into practice in a robust, pragmatic monitoring system.

Recommendations for further work include the following:

- *WARMS enhanced*: inclusion of additional field metrics pertaining to ecological/ecosystem integrity and biodiversity conservation.

- *WARMS extended*: increase the number of monitoring sites to (a) include parts of the landscape more vulnerable to change and (b) increase the density of spatial coverage within both the pastoral and non-pastoral (e.g. conservation estate) rangelands. The aim is to better sample the spatial heterogeneity of the range landscape including vulnerable or high value areas such as ecotones and ecojunctions, key habitats and other landscape structures.

- *WARMS extended plus*: investigate the integration of complementary remotely-sensed attributes and WARMS ground monitored attributes for landscape- or catchment-scale ecological assessment; the SRC indices could provide reference points for calibration of the remotely-sensed data.

- Investigate the inclusion of more direct, monitoring site-specific measures of the drivers of change, particularly total grazing pressure and climate in the pastoral areas, and additional measures of threatening processes in the conservation estate (e.g. visitor impacts).

- *WARMS web portal*: develop a web-based information delivery system for use by pastoralists, land and natural resource managers and other interested people.

- Investigate in detail, relationships between the SRC indices and various vegetation-soil-landscape-catchment spatial entities; aspects include the response sensitivity to drivers of change (e.g. climate, grazing, fire, and flood) and the effect of feedback and time-lag inherent in plant – soil interactions. This is part of the required rigorous testing and verification of the SRC indices against independent assessments of ecological condition.

- Investigate the use of SRC indices for potential land use assessments.

- Investigate analytical methods and models to predict range and ecological condition.

Each of the items of recommended research is a difficult undertaking. Underpinning the difficulty is the perennial problem which confronts most ecologists and that is, to reliably establish cause and effect. The difficulty is compounded in monitoring because there is no or very limited control of all the variables, unlike the situation with controlled experiments. Given that there are an enormous number of variables – literally, millions of small-scale events may become collective drivers of large-scale processes – there are very substantial difficulties in inferring chains of causation from observed correlations between certain variables. Therefore, putative causal factors need to be continually tested; this is the scientific method to advance knowledge.

7 References

Chapter 7: REFERENCES

AHC 1996, *Australian Heritage Charter for the conservation of places of natural heritage significance: standards and principles*, Australian Heritage Commission, Australian Committee for IUCN, Canberra.

Alexander, N. (ed.) 1996, *Australia: State of the Environment 1996*, CSIRO, Melbourne.

Allen, A. D. 1997, *Groundwater: The Strategic Resource - a Geological perspective of groundwater occurrence and importance in Western Australia*, The Geological Survey of Western Australia, Perth WA, Report 50.

Anon. 1973, 'Arid Shrublands', in *Proceedings of the Third Workshop of the United States / Australia Rangelands Panel*, ed. DN Hyder, Society for Range Management, Tucson, Arizona, p. 148.

Anon. 1974, 'Plant Morphogenesis as the Basis for Scientific Management of Range Resources', in *Proceedings of the Workshop of the United States-Australia Rangelands Panel, March-April 1971*, eds. KW Kreitlow & RH Hart, US Department of Agriculture, Miscellaneous Publication No 1271, Berkeley, California, p. 232.

Anon. 1977, 'The Impact of herbivores on arid and semi-arid rangelands. Proceedings of the Second United States-Australia Rangeland Panel, 1972', Australian Rangeland Society, Adelaide, South Australia, p. 376.

Anon. 1978, 'Proceedings of the First International Rangeland Congress, August 1978', ed. DN Hyder, Society for Range Management, Denver, Colorado, p. 740.

Anon. 1979, 'Rangeland Ecosystem Evaluation and Management. Proceedings of the Fourth Workshop of the United States-Australia Rangeland Panel, 1974', ed. KMW Howes, Australian Rangeland Society, Alice Springs, Northern Territory, p. 276.

Anon. 1986, 'Proceedings of the Second International Rangeland Congress, May 1984', eds. PJ Joss, PW Lynch & OB Williams, CSIRO Divisions of Wildlife and Rangelands Research and Groundwater Research, Adelaide, South Australia.

Anon. 2001, *Rangelands - Tracking Changes Australian Collaborative Rangeland Information System*, National Heritage Trust & National Land & Water Resources Audit.

Anon. 2006a, *Australian State of the Environment 2006*, Independent Report to the Australian Government Minister for the Environment and Heritage, Canberra.

Anon. 2006b, *Western Australia Annual Pastoral Land Condition Report 2005/2006*, Report prepared for the Pastoral Lands Board by the Department of Agriculture and Food, Perth.

Austin, M. P. 2002, 'Spatial prediction of species distribution: an interface between ecological theory and statistical modelling', *Ecological Modelling,* vol. 157, pp. 101-118.

Bastin, G. N., Chewings, V. H., Ludwig, J., Eager, R. W., Liedloff, A. C. & Karfs, R. A. 2002, 'Monitoring Landscape Function with Remotely-Sensed Imagery', *Range Management Newsletter,* vol. March 2002, pp. 7-8.

Bastin, G. N., Ludwig, J., Eager, R. W. & Liedloff, A. C. 2004, 'Potential of multi-scale video imagery to indicate the leakiness of rangelands', *Range Management Newsletter,* vol. 04, no. 1, pp. 1-5.

Battye, J. S. (ed.) 1915, *The History of the North West of Australia,* Facsimile Edition 1985, Hesperian Press edn, V. K. Jones & Co, Perth.

Bennett, B. 1997, 'Water points: where pastoralism and biodiversity meet', *ECOS,* vol. 92, pp. 10-14.

Bennett, J., Sanders, N., Moulton, D., Phillips, N., Lukacs, G., Walker, K. & Redfern, F. 2002, *Guidelines for Protecting Australian Waterways*, Land and Water Australia.

Burnside, D. G. 1991, *How People Interpret Monitoring Data*, Western Australian Department of Agriculture, Perth.

Burnside, D. G. & Faithfull, E. 1993, 'Judging range trend: interpretation of rangeland monitoring data drawn from sites in the Western Australian shrublands', *Rangel. J.,* vol. 15, no. 2, pp. 247-269.

Burrough, P. A. 1996, *Principles of Geographical Information Systems for Land Resources Assessment*, Clarendon Press, Oxford.

Carneggie, D. M., Wilcox, D. G. & Hacker, R. B. 1971, *The Use of Large Scale Aerial Photographs in the Evaluation of Western Australian Rangelands*, Department of Agriculture of Western Australia, Perth, Technical Bulletin No10.

Caswell, H., Takada, T. & Hunter, C. M. 2004, 'Sensitivity analysis of equilibrium in density-dependent matrix population models', *Ecology Letters,* vol. 7, pp. 380-387.

Cunningham, G. M. 1976, 'Some concepts for range assessment in Australia', *Aust. Rangel. J.,* vol. 1, no. 1, pp. 60-63.

Curry, P. 2003, *Summary Report on Early Measures of Biodiversity for Carbon Sequestration by Woodland Revegetation - Rehabilitation at Sturt Meadows station, North-Eastern Goldfields*, Vital Options Consulting for Japan Science and Technology Corporation, Perth.

Daly, F. 2004, *The associations of birds with vegetation communities at Sunrise Dam Gold Mine - Summary Report*, University of Western Australia.

D'Odorico, P. & Porporato, A. (eds.) 2006, *Dryland Ecohydrology*, Springer, Dordrecht, The Netherlands.

Duckett, N. J., Holm, A. M. & Thomas, P. W. E. 1996, *The Western Australian Rangeland Monitoring System*, Department of Agriculture Western Australia, Perth, National Landcare Program Project 89/W/M3.

Easterling, M. R., Ellner, S. P. & Dixon, P. M. 2000, 'Size-specific sensitivity: applying a new structured population model', *Ecology,* vol. 81, no. 3, pp. 694-708.

Fagan, B. 2004, *The Long Summer: How Climate Changed Civilisation,* First edn, Granta Publications, London.

Farina, A. 2006, *Principles and Methods in Landscape Ecology,* 2nd edn, Springer, Dordrecht, Netherlands.

Flannery, T. 2005, *The Weather Makers - The History & Future Impacts of Climate Change,* First edn, The Text Publishing Company, Melbourne.

Fyfe, W. V. 1940, *Report of Royal Commission appointed to inquire into and report upon the financial and economic position of the pastoral industry in the leasehold areas in Western Australia*, Government of Western Australia, Perth.

Hacker, R. 1973, 'Range assessment theory and methods', in *Second Rangeland Management Conference*, Department of Agriculture, Carnarvon, pp. 8-31.

Hacker, R. B. 1984, 'Vegetation dynamics in a grazed mulga shrubland community. The mid-storey shrubs', *Aust. J. Bot.,* vol. 32, pp. 239-249.

Hacker, R. B. 1986, 'Analysis of WARMS data - some alternatives', in *Rangeland Management Branch Conference*, Department of Agriculture Western Australia, p. 7.

Hacker, R. B. 1992, 'The development of rangeland monitoring in Western Australia', in *Range Monitoring Workshop, 5th Australian Soil Conservation Conference*, Department of Agriculture Western Australia, pp. 31-34.

Holm, A. M. 1983, *A Review of Range Trend Assessment in the Shrubland Pastoral Areas of Western Australia*, Department of Agriculture, Perth.

Holm, A. M. 1993a, 'WARMS at the crossroads', *Range Management Newsletter,* vol. 93, no. 2, pp. 18-19.

Holm, A. M. 1993b, 'The Western Australian rangeland monitoring program - an overview', *Plant Dynamics and Interpretation in Rangeland Ecosystems Workshop*, pp. 13-16.

Holm, A. M. 1993c, 'The Western Australian rangeland monitoring program and its application in shrublands', *Plant Dynamics and Interpretation in Rangeland Ecosystems Workshop, Yanchep*, pp. 21-24.

Holm, A. M. 2000, *A study of degradation processes at patch to landscape scale within the arid shrubland of Western Australia*, PhD, University of Western Australia.

Holm, A. M., Burnside, D. G. & Mitchell, A. A. 1987, 'The development of a system for monitoring trend in range condition in the arid shrublands of Western Australia', *Aust. Rangel. J.,* vol. 9, no. 1, pp. 14-20.

Holm, A. M., Curry, P. J. & Wallace, J. F. 1984, 'Observer differences in transect counts, cover estimates and plant size measurements on range monitoring sites in an arid shrubland', *Aust. Rangel. J.,* vol. 6, no. 2, pp. 98-102.

Holm, A. M., Watson, I. W., Loneragan, W. A. & Adams, M. A. 2002, 'Loss of patch scale heterogeneity on primary productivity and rainfall-use efficiency in Western Australia', *Basic Appl. Ecol.,* vol. 4, pp. 569-578.

Hunt, L. 2001, 'Heterogeneous grazing causes local extinction of edible perennial shrubs: a matrix analysis', *Journal of Applied Ecology*, pp. 238-252.

James, C. 2004, 'Biodiversity Monitoring in Rangelands', in *"Living in the Outback" 13th Biennial Conference*, Australian Rangeland Society, Alice Springs, pp. 176-182.

James, C. D. 2003, 'Response of vertebrates to fenceline contrasts in grazing intensity in semi-arid woodlands of eastern Australia', *Austral Ecology,* vol. 28, pp. 137-151.

Jennings, J. N. & Mabbutt, J. A. 1986, 'Physiographic outlines and regions', in DN Jeans (ed.), *Australia - a geography: the natural environment*, vol. 1, Sydney University Press, Sydney, pp. 81-96.

Johnson, S. L., Commander, D. P. & O'Boy, C. A. 1999, *Groundwater Resources of the Northern Goldfields, Western Australia*, ISBN 0 7309 7434 0, Water and Rivers Commission, HG 2.

Kollmann, J. 2000, 'Dispersal of fleshy-fruited species: a matter of spatial scale?' *Perspectives in Plant Ecology, Evolution and Systematics,* vol. 3, no. 1, pp. 29-51.

Krebs, C. J. 1994, *Ecology. The Experimental Analysis of Distribution and Abundance,* Fourth edn, Harper Collins, New York.

Lamacraft, R. R. 1978, 'Observer errors in sampling ecological variables for range condition assessment', in *Proceedings of the First International Rangeland Congress, August 1978*, ed. DN Hyder, Society for Range Management, Denver, Colorado, pp. 514-516.

Lechmere-Oertel, R. G., Cowling, R. M. & Kerley, G. I. H. 2005, 'Landscape dysfunction and reduced spatial heterogeneity in soil resources and fertility in semi-arid succulent thicket, South Africa', *Austral Ecology,* vol. 30, pp. 615-624.

Lendon, C. & Lamacraft, R. R. 1976, 'Standards for testing and assessing range condition in central Australia', *Aust. Rangel. J.,* vol. 1, no. 1, pp. 40-48.

Lindenmayer, D. & Burgman, M. 2005, *Practical Conservation Biology,* First edn, CSIRO Publishing, Melbourne.

Lindenmayer, D. B. & Fischer, J. 2006, *Habitat Fragmentation and Landscape Change: An Ecological and Conservation Synthesis*, CSIRO Publishing, Melbourne.

Ludwig, J., Tongway, D., Freudenberger, D., Noble, J. & Hodgkinson, K. 1997, *Landscape Ecology, Function and Management - Principles from Australia's Rangelands*, CSIRO Publishing, Melbourne, Victoria.

Martin, T. G. & Possingham, H. P. 2005, 'Predicting the impact of livestock grazing on birds using foraging height data', *Journal of Applied Ecology,* vol. 42, pp. 400-408.

McGoggan, G. 1997, *History of Drilling in Australia*, The AusIMM, Melbourne.

McKell, C. M. & Goodin, J. R. 1973, 'US arid shrublands in perspective', in *Arid Shrublands Proceedings of the Third Workshop of the United States / Australia Rangelands Panel*, ed. DN Hyder, Society for Range Management, Tucson, Arizona, pp. 12-18.

McKenzie, N., Jacquier, D., Isbell, R. & Brown, K. 2004, *Australian Soils and Landscapes: an illustrated compendium*, CSIRO Publishing, Melbourne.

McKeon, G. M., Hall, W. B., Henry, W. B., Stone, G. S. & Watson, I. W. 2004, *Pasture Degradation and Recovery in Australia's Rangelands. Learning from History*, Queensland Department of Natural Resources, Mines and Energy, Brisbane, QNRME 04130.

McTainsh, G. H. & Boughton, W. C. 1993, *Land Degradation Processes in Australia*, 1993, Addison Wesley Longman Australia Pty Ltd.

Milton, S. J., Wilson, J. R. U., Richardson, D. M., Seymour, C. L., Dean, W. R. J., Iponga , D. M. & Roches, S. 2007, 'Invasive alien plants infiltrate bird-mediated shrub nucleation processes in arid savanna', *Journal of Ecology,* vol. OnlineEarly Articles doi: 10.1111/j.1365-2745.2007.01247.x, p. 14.

Mitchell, A. A., McCarthy, R. C. & Hacker, R. B. 1988, *A range inventory and condition survey of part of the Western Nullarbor Plain, 1974*, Department of Agriculture, Perth, No 47.

Mitchell, R., Mitchell, K. & Alchin, M. 2005, 'We cannot afford yesterday's losses', *Pastoral Memo Southern Rangelands,* vol. 11, no. 2, pp. 12-15.

Moore, R. M. 1973, 'Australian arid shrublands', in *Proceedings of the Third Workshop of the United States / Australia Rangelands Panel, March-April 1973*, ed. DN Hyder, Society for Range Management, Tucson, Arizona, pp. 6-11.

Morrissey, J. G. 1976, 'Photography and Range Site Monitoring', vol. Rangeland Bulletin No 24, September 1976, p. 7.

National Research Council 1994, *Rangeland Health: New Methods to Classify, Inventory and Monitor Rangelands*, National Academy Press, Washington DC.

Noble, I. R. 1979, 'The assessment of range trend and utilisation in Australia', in *Proceedings of the Fourth Workshop of the United States-Australia Rangeland Panel, 1974*, ed. KMW Howes, Australian Rangeland Society, Alice Springs, Northern Territory, pp. 120-136.

Nusser, S. M., Breidt, F. J. & Fuller, W. A. 1998, 'Design and estimation for investigating the dynamics of natural resources', *Ecological Applications,* vol. 8, no. 2, pp. 234-245.

Perry, R. A. 1977, 'Rangeland management for livestock production in semi-arid and arid Australia', in *Proceedings of the Second United States-Australia Rangeland Panel, 1972*, Australian Rangeland Society, Adelaide, South Australia, pp. 311-316.

Pringle, H. J. R. 1998, 'Environmental auditing beyond 'range condition': a Western Australian perspective', *Journal of Arid Land Studies,* vol. 7S, pp. 35-38.

Pringle, H. J. R. 2004, 'Biodiversity monitoring or biodiversity management systems: which is the cart and which is the horse?' in *Living in the Outback*, Alice Springs, pp. 195-200.

Pringle, H. J. R. & Coleman, B. 2006, 'Is the monitoring finger on the pulse or on the toenail in Outback Western Australia?' Perth, p. 34,

Pringle, H. J. R. & Tinley, K. 2003, 'Are we overlooking critical geomorphic determinants of landscape change in Australian rangelands?' *Ecological Management and Restoration,* vol. 4, no. 3, pp. 180 - 186.

Pringle, H. J. R., Tinley, K., Brandis, T., Hopkins, A. J. M., Lewis, M. & Taylor, L. 2003, 'The Gascoyne-Murchison Strategy: A people-centred approach to conservation in arid Western Australia', *Proceedings of the VII International Rangelands Congress*, pp. 213-223.

Pringle, H. J. R., Van Vreeswyk, A. M. E. & Gilligan, S. A. 1994, *An Inventory and condition survey of the north-eastern Goldfields, Western Australia*, Department of Agriculture, WA, 87 Agdex 320/10.

Pringle, H. J. R., Watson, I. W. & Tinley, K. L. 2006, 'Landscape improvement, or ongoing degradation - reconciling apparent contradictions from the arid rangelands of Western Australia', *Landscape Ecology,* vol. 21, no. 8, pp. 1267-1279.

Reid, J. & Fleming, M. 1992, 'The Conservation Status of Birds in Arid Australia', *Rangeland Journal,* vol. 14, no. 2, pp. 65-91.

Reynolds, J. F. & Stafford Smith, D. M. (eds.) 2002, *Global Desertification: Do Humans Cause Deserts?,* Report of the 88th Dahlem Workshop, Berlin, 10-15 June 2001 edn, Dahlem University Press, Berlin, Germany.

Roberts, B. R. 1992, 'Managing the unmanageable - building environmental feedback into pastoral systems', *5th Australian Soil Conservation Conference, Range Monitoring Workshop,* vol. 7, pp. 7-13.

Rosenberg, K., Boland, J., Tiver, F. & Watson, I. 2005, 'Application of the Vandermeer-Moloney Algorithm for determination of category size to Australian native plants', *submitted*.

Ross, L. 1991, *A historical analysis of the development of the pastoral industry in the shires of the North Eastern Goldfields of WA*, BBus (Agric), Curtin University of Technology.

Russell, P. & Fletcher, W. 2003, 'Relative palatability of selected perennial plants in the southern rangelands of Western Australia - results of a survey of rangeland practitioners', *Range Management Newsletter,* vol. 03, no. 3, (November 2003), p. 9 pages plus chart appendix.

Russell, P. J. & Watson, I. W. 2006, 'History of rangeland monitoring in Western Australia', Australian Rangeland Society, Alice Springs, NT.

Saunders, D. A. & Curry, P. J. 1990, 'The impact of agriculture and pastoral industries on birds in the southern half of Western Australia: past, present and future', in *Ecology 1990*, Ecological Society of Australia, pp. 303-321.

Sharp, B. R. & Bowman, D. M. J. S. 2004, 'Net woody vegetation increase confined to seasonally inundated lowlands in an Australian tropical savanna, Victoria River District, Northern Territory', *Austral Ecology,* vol. 29, no. 6, pp. 667 - 683.

Silvertown, J. W. & Lovett-Doust, J. 1993, *Introduction to Plant Population Biology,* Third edn, Blackwell Scientific Publications, Oxford.

Skelton, J. & Skelton, J. 2007, 'Sustainable grazing in the rangelands- a case study in the Mitchell grass downs', *Range Management Newsletter,* vol. 07, no. 2, pp. 6-9.

Southgate, R., Allan, G. & Ostendorf, B. 2006, 'An examination of the Stafford Smith - Morton ecological model: a case study in the Tanami Desert, Australia', *The Rangeland Journal,* vol. 28, pp. 197-210.

Stafford Smith, D. M. & Morton, S. R. 1990, 'A framework for the ecology of arid Australia', *J. Arid Environments,* vol. 18, pp. 255-278.

Strickler, G. S. & Stearns, F. W. 1963, 'The determination of plant density', in *Range Research Methods: A Symposium, May 1962*, US Department of Agriculture, Miscellaneous Publication No 940, Denver, Colorado, pp. 30-40.

Tassicker, A. L., Kutt, A. S., Vanderduys, E. & Mangru, S. 2006, 'The effects of vegetation structure on the birds in a tropical savanna woodland in north-eastern Australia', *The Rangeland Journal,* vol. 28, pp. 139-152.

Tester, M., Paton, D. C., Reid, N. & Lange, R. T. 1987, 'Seed dispersal by birds and densities of shrubs under trees in arid South Australia', *Transactions Royal Society of South Australia,* vol. 111, no. 1, pp. 1-5.

Thackway, R. & Cresswell, I. D. (eds.) 1995, *An Interim Biogeographic Regionalisation for Australia: a Framework for Setting Priorities in the National Reserves System Cooperative Program,* Version 4.0, 31 March 1995 edn, Australian Nature Conservation Agency, Canberra, ACT.

Thomas, D. S. G. 1989, *Arid Zone Geomorphology*, 1989, Bellhaven Press.

Tinley, K. 1991, 'Towards harmony with the land: the drainage basin ecosystem context', *Environmental Planning and Management,* vol. 2, no. 5, p. 3.

Tinley, K. 2005, 'Perch-base thickets and berry birds: keystones of arid Australia (abstract)', in *4th International Symposium on Frugivores and Seed Dispersal, July 2005*, Griffith University, Brisbane.

Tinley, K. L. 1977, *Framework of the Gorongosa Ecosystem, Mocambique*, DSc, University of Pretoria.

Tinley, K. L. 1982, 'The influence of soil moisture balance on ecosystem patterns in southern Africa', in BJ Huntley & BH Walker (eds.), *Ecological Studies: Ecology of Tropical Savannas*, vol. 42, Springer-Verlag, Berlin, pp. 175 -192.

Tiver, F. & Andrew, M. H. 1997, 'Relative effects of herbivory by sheep, rabbits, goats and kangaroos on recruitment and regeneration of shrubs and trees in eastern South Australia', *Journal of Applied Ecology,* vol. 34, no. 4, pp. 903-914.

Tongway, D. J. 1990, 'Soils research on the Boolathana grazing trial, Carnarvon, WA', *6th Australian Rangeland Conference*, pp. 320-322.

Tongway, D. J. 1992, 'Identification of ecosystem processes as a basis for range monitoring methods', *5th Australian Soil Conservation Conference, Range Monitoring Workshop,* vol. 7, p. 20.

Tongway, D. J. 1994, *Rangeland Soil Condition Assessment Manual*, CSIRO Division of Wildlife & Ecology, Canberra ACT.

Tongway, D. J. & Greene, R. S. B. 1989, *The Role of Pastoral Management on Soil Productive Potential in Rangelands*, CSIRO, Deniliquin.

Tongway, D. J. & Hindley, N. 2003, 'Landscape Function Analysis: A System for Monitoring Rangeland Function', in *VII International Rangeland Congress*, ed. NP Allsop, A R; Milton, S J; Kirkman K P; Kerley, G I H; Hurt, C R; Brown, C J, Durban South Africa, pp. 663 - 667.

Tongway, D. J. & Hindley, N. L. 1995, *Manual for Soil Condition Assessment of Tropical Grasslands*, CSIRO Division of Wildlife and Ecology, Canberra.

Tongway, D. J. & Hindley, N. L. 2004, *Landscape Function Analysis Manual: Procedures for Monitoring and Assessing Landscapes with Special Reference to Minesites and Rangelands, Version 3.1,* CD-ROM, CSIRO Sustainable Ecosystems, Canberra.

Vallentine, J. F. 1990, *Grazing Management,* First edn, Academic Press, San Diego.

Vesk, P. A. & Westoby, M. 2001, 'Predicting plant species' responses to grazing', *Journal of Applied Ecology,* vol. 38, pp. 897 - 909.

Ward, J. V., Tockner, K. & Schiemer, F. 1999, 'Biodiversity of floodplain river ecosystems: ecotones and connectivity', *Regulated Rivers: Research and Management,* vol. 15, pp. 125-139.

Watson, I. W. 1997, *Continuous and episodic demography of arid zone shrubs in Western Australia, 1983-1993*, PhD, Macquarie University.

Watson, I. W. 2002, 'Thirty years of monitoring Western Australia's rangelands', *Land Management Society,* vol. 1, no. 6, pp. 15-16.

Watson, I. W. 2003, 'Preventing desertification and promoting rehabilitation in Western Australian semi-arid rangelands at the individual property scale', in *Global Perspective in Range Rehabilitation and Prevention of Desertification. The 2003 Obihiro Asia and the Pacific Seminar on Education for Rural Development*, ed. J Takahashi, Obihiro University of Agriculture and Veterinary Medicine, Hokkaido, Japan, pp. 33 - 44.

Watson, I. W. & Holm, A. M. 1990, 'The benefits of palatable shrubs for wool production in a semi-arid environment', *6th Australian Rangeland Society Conference, Carnarvon*, pp. 25-34.

Watson, I. W. & Novelly, P. 2004, 'Making the biodiversity monitoring system sustainable: Design issues for large-scale monitoring systems', *Austral Ecology,* vol. 29, pp. 16-30.

Watson, I. W., Novelly, P. E. & Thomas, P. W. E. in press, 'Monitoring changes in pastoral rangelands - the Western Australian Rangeland Monitoring System (WARMS)', *The Rangeland Journal*.

Watson, I. W., Thomas, P. W. E. & Fletcher, W. J. 2007, 'The first assessment, using a rangeland monitoring system, of change in shrub and tree populations across the arid shrublands of Western Australia', *The Rangeland Journal,* vol. 29, no. 1, pp. 25-37.

Webb, M. 1993, 'In search of grass and gold: the invasion of the arid lands of Western Australia', in *Goldfields International Conference on Arid Landcare*, Kalgoorlie, Western Australia, pp. 1-29.

West, N. E. 2003, 'History of rangeland monitoring in the USA', *Arid Land Research and Management,* vol. 17, no. 4, pp. 495-545.

Westoby, M. 1979/80, 'Elements of a theory of vegetation dynamics in arid rangelands', *Israel Journal of Botany,* vol. 28, pp. 169-194.

Whitehead, P., Woinarski, J. C. Z., Fisher, A., Fensham, R. & Beggs, K. 2001, *Developing an Analytical Framework for Monitoring Biodiversity in Australia's Rangelands Project 3 - Theme 4 (Rangelands Monitoring)*, A Report by the Tropical Savannas CRC for the National Land and Water Resources Audit.

Wilcox, D. G. 1974, 'Morphogenesis and management of woody perennials in Australia', in *Proceedings of the Workshop of the United States-Australia Rangelands Panel, March-April 1971*, eds. KW Kreitlow & RH Hart, US Department of Agriculture, Miscellaneous Publication No 1271, Berkeley, California, p. 232.

Wilcox, D. G. 1988, 'Fair use and a fair go', *Rangel. J.,* vol. 10, no. 2, pp. 76-81.

Wilcox, D. G. & Burnside, D. G. 1994, 'Land administration in the rangelands: what for, who for and how?' *Rangel. J.,* vol. 16, no. 2, pp. 298-310.

Wilcox, D. G. & McKinnon, E. A. 1972, *A Report on the Condition of the Gascoyne Catchment*, Department of Agriculture and Department of Lands & Survey.

Williams, O. B., Suijdendorp, H. & Wilcox, D. G. 1980, 'The Gascoyne Basin', in *United Nations Conference on Desertification*, eds. MR Biswas & AK Biswas, Pergamon Press, Nairobi, 1977, pp. 3-106.

Woinarski, J. C. Z. & Ash, A. J. 2002, 'Responses of vertebrates to pastoralism, military land use and landscape position in an Australian tropical savanna', *Austral Ecology,* vol. 27, pp. 311-323.

Young, A. & Young, R. 2001, *Soils in the Australian Landscape,* First edn, Oxford University Press, Oxford.

Zar, J. H. 1999, *Biostatistical Analysis,* Fourth edn, Prentice-Hall, New Jersey.

Ziembicki, M. 2003, 'Tracking nomadic birds and habitat health', *ECOS,* vol. 117.

APPENDIX

BERRY BEARING BROWSE PLANTS

Alphabetical list of 44 fruit-bearing browse plants recorded from the Gascoyne, Murchison, Goldfields and Nullarbor arid scrublands of Western Australia by Dr Ken Tinley. Fruits include berries, coloured arillates and seed mimics of these (e.g. some plants in the *Brachychiton* and *Pittosporum* genera).

List kindly provided to Peter Russell, February 2005.

Acacia oswaldii	*Jasminum lineare*
Acacia paraneura	*Lycium australe*
Acacia sclerosperma	*Nitraria billardierei*
Acacia sibilans	*Pimelea microcephala*
Acacia tetragonophylla	*Pittosporum phylliraeoides*
Alectryon oleifolius	*Rhagodia baccata*
Alyxia buxifolia	*Rhagodia crassifolia*
Atriplex semibaccata	*Rhagodia drummondii*
Brachychiton gregorii	*Rhagodia eremaea*
Canthium attenuatum	*Rhagodia latifolia*
Canthium latifolium	*Rhagodia preissii*
Canthium lineare	*Rhagodia spinescens*
Capparis lasiantha	*Rhagodia ulicina*
Capparis mitchellii	*Santalum acuminatum*
Capparis spinosa	*Santalum lanceolatum*
Chenapodium gaudichaudianum	*Santalum murrayanum*
Einadia nurtans	*Santalum spicatum*
Enchylaena tomentosa	*Scaevola spinescens*
Eremophila longifolia	*Scaevola tomentosa*
Eremophila pantonii	*Solanum orbiculatum*
Exocarpos aphyllus	*Spartothamnella teucriiflora*
Exocarpos sparteus	*Stylobasium spathulatum*

NOTE: there are also 10 different berry-bearing mistletoes in the region, many of which are heavily browsed when within reach by goats and camels.

Amyema spp. (7 species)
Lysiana spp. (3 species).