DECLARATION

I declare that this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge it does not contain any materials previously published or written by another person except where due reference is made in the text.

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Date 25th of Oct 2007

Terrestrial Survey and Remotely-sensed Methods for Detecting the Biological Soil Crust Components of Rangeland Condition

by

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DEFINITIONS, TERMS, ABBREVIATIONS AND ACRONYMS

As the essence of this study is multidisciplinary there are a number of terms such as rangeland management, monitoring, inventory, ecology, soil surface components, biological soil crusts, geographic information systems, remote sensing, and statistics which this study discusses. These terms are sometimes used interchangeably and can lead to confusion, particularly between disciplines, with others. Following is a glossary of terms and acronyms used in this research for clarification.

Accuracy: the closeness of a measured or computed value to its true value and is dependent on having a good measuring device or system (Krebs, 1989). Accuracy cannot be determined from a sample, and usually remains unknown.

Accuracy assessment: the comparison of a classification to geographical data that is assumed to be true. Usually, the assumed-true data are derived from ground-truthing (Leica Geosystems, 2004a).

ACRES (Digital Catalogue): is a database of archived satellite data acquisitions over Australia from the Landsat, ERS, RADARSAT and JERS earth observation satellites.

AGD94: Australian Geodetic Datum / Geocentric Datum of Australia 1994

Albedo: a measure of the energy reflected off a surface. Dark surfaces have a lower albedo than light surfaces; therefore, light surfaces absorb less energy than dark surfaces (Belnap *et al.*, 2001b).

Algae: Non-vascular photosynthetic plant-like organisms, they are informally divided into groups by their dominant pigments (i.e., green, brown, red, etc.).

Annual plants: a plant completing its life cycle in a year or less

ASTER: Advanced Space borne Thermal Emission and Reflection Radiometer

AVHRR: Advanced Very High Resolution Radiometer data. Small-scale imagery produced by an NOAA polar orbiting satellite. It has a spatial resolution of 1.1 × 1.1 km or 4 × 4 km (Leica Geosystems GIS & Mapping LLC, 2003).

AVIRIS: Airborne Visible Infrared Imaging Spectrometer

Azimuth:an angle measured clockwise from a meridian, going north to east (Leica Geosystems GIS & Mapping LLC, 2003).

Band: a set of data file values for a specific portion of the electromagnetic spectrum of reflected light or emitted heat (red, green, blue, near-infrared, infrared, thermal, etc.), or some other user-defined information created by combining or enhancing the original bands, or creating new bands from other sources. Sometimes called channel (Leica Geosystems, 2004a).

Bare Soil: area or components of the rangeland surface which is covered by soil particles smaller than 1/4 inch diameter (soil particle) (Society for Range Management, 1999).

BCL: Black Common Lichens

BCM: Black Common Mosses

Bidirectional reflectance distribution function (BRDF): BRDF is the ratio of the reflected radiance to collimated incident radiant flux per unit area and describes the unique scattering properties of the surface, independent of the anisotropy of the incident radiation distribution (Kimes & Kirchner, 1982).

Bryophytes: tiny plants from the phylum Bryophyta such as mosses, liverworts and hornworts without vascular tissues or true roots, stems, and leaves (Belnap *et al.*, 2001b).

BSC: Biological Soil Crusts

BSCI: Biological Soil Crust Index

Canopy cover: the proportion of ground covered by a vertical projection of the outermost perimeter of the natural spread of foliage or plants.

CASI: Compact Airborne Spectrographic Imager

Climax: the final stage of succession that continues to occupy an area as long as climate and soil conditions remain unchanged.

CI: Crust Index

Crustose lichens: lichens that form a crust like growth form that is closely applied to the substrate (Belnap *et al.*, 2001b).

CSIRO: Australian Commonwealth Scientific and Industrial Research Organization

Cyanobacteria: "Blue-green" algae; prokaryotic, photosynthetic organisms that generally have a blue-green tint and lack chloroplasts (Belnap *et al.*, 2001b).

Cyanolichen: lichen that contains a cyanobacterium as its photobiont (Belnap *et al.*, 2001b).

Datum: in a topocentric coordinate system, the tangential plane at the centre of the image on the Earth ellipsoid, on which the three perpendicular coordinate axes are defined (Leica Geosystems, 2004a).

Detectability: is the ability of an imaging system to record the absence or presence of an object (Brook *et al.*, 2001).

Detector: a detector is the device in a sensor system that records electromagnetic radiation. For example, in the sensor system on the Landsat TM scanner there are 16 detectors for each wavelength band (except band 6, which has 4 detectors) (Leica Geosystems, 2004a).

DEM: Digital Elevation Model: are digital files consisting of points of elevations, sampled systematically at equally spaced intervals.

DVI: Difference Vegetation Index

EMR: ElectroMagnetic Radiation

Digital Number: (DN) variation in pixel intensity due to composition of what it represents. For example, the DN of water is different from that of land. DN is expressed in a value typically from 0-255 (Leica Geosystems, 2004a).

Endmember: an endmember is the set of data values defining one component in a mixture. For instance, in remote sensing a spectral endmember is the spectral signature of a ground component such as photosynthetic vegetation, litter, soil or rock. Often, the term of endmember is used to refer to a ground component itself.

Ephemeris: any tabular statement of the assigned places of a celestial body for regular intervals. For example, the solar ephemeris provides the exact location of the sun at any given time of the day or year (Jensen, 1996).

ETM+: Enhanced Thematic Mapper plus is a multispectral scanning radiometer that was carried on board Landsat 7.

Exoatmospheric: Out of atmosphere (radiance at out of the atmosphere)

FAO: Food and Agricultural Organization (United Nations)

Foliose lichens: lichens that are leaf-like in growth form, flattened with definite upper and lower surfaces, and usually loosely attached to the substrate (Belnap *et al.*, 2001b).

Forb: a plant with a non-woody stem, that is not a grass or grass-like plant.

Frequency: is defined as the relation between the number of sampling units in which the species is present and the total number of sampling units (Bonham, 1989).

Fruticose lichens: Lichens with three dimensional growth forms that are ropey or branching and do not have definite upper and lower surfaces (Belnap *et al.*, 2001b).

Fungi: Non-photosynthetic multicellular organisms that are either saprophytic or parasitic.

GCP: Ground Control Point

Gelatinous lichens: lichens that are non-stratified (algal and fungal layers are not distinct) and that have a jelly like appearance when moistened. All gelatinous lichens have cyanobacteria as their phytobiont (Belnap *et al.*, 2001b).

Geocoding: geographical referencing or coding of data (Jensen, 1996)

Geographic Information System (GIS): a powerful set of tools for collecting, storing,

retrieving, transforming and displaying spatial data from the real world (Burrough, 1986).

Georeferencing: assigning map coordinates to image data

GPS: Global Positioning System

Ground-truthing: the acquisition of knowledge about the study area from field work, analysis of aerial photography, personal experience, etc. Ground truth data are considered to be the most accurate (true) data available about the area of study (Leica Geosystems, 2004a).

Grazing gradient: grazing gradients are spatial patterns in soil or vegetation characteristics resulting from a gradient of grazing intensity (usually structured at a watering point) and which are symptomatic of land degradation (Pickup & Chewings, 1994).

Green algae: photosynthetic unicellular and multicellular organisms that lack true tissue differentiation (Belnap *et al.*, 2001b).

Ground cover: the percentage of material, other than bare ground, covering the land surface. It may include live and standing dead vegetation, biological soil crusts, litter, cobble, gravel, stones and bedrock. Ground cover plus bare ground would total 100 percent/cover by plants, litter, and rocks in a vegetation type.

Habitat: the sum total of environmental conditions of a specific place occupied by a wildlife species or a population of such species.

Heterogeneity of variance: a situation in which samples are drawn from populations having different variances.

Hyperspectral: produces a colour image containing data from a very large number of spectral wavelengths or the imaging sensors that record multiple bands of data, such as the AVIRIS with 224 bands (Leica Geosystems, 2004a).

Indicator: components of a system whose characteristics (e.g., presence or absence, quantity, distribution) are used as an index of an attribute (e.g., rangeland health) that are too difficult, inconvenient, or expensive to measure.

Indices: the formulae used to create output images by mathematically combining the DN values of different bands (Leica Geosystems, 2004a).

Infiltration: the entry of water into the soil.

Infrared (IR): region of the electromagnetic spectrum between approximately 700 nm and 1mm. This can be further sub-divided into the near-infrared (700-1300 nm), mid-infrared (1300-3000 nm) and thermal infrared (3000 nm to 1 mm) (PP Systems, 1999).

Integration time: the duration that photodiode array is exposed to light during measurement. This is comparable to the "exposure time" when operating a photographic camera (PP Systems, 1999).

IPVI: Infrared Percentage Vegetation Index

Irradiance: (radiant flux density incident on a surface) is the radiant flux incident on a receiving surface from all directions per unit of area. Unit: W m^{-2} nm^{-1}(ASD, 1999).

JPL: Jet Propulsion Laboratory (California Institute of Technology)

Landsat: a series of Earth-orbiting satellites that gather MSS, TM and +ETM imagery, operated by EOSAT (Leica Geosystems, 2004a).

Landscape: an area of interacting ecosystems where patterns are repeated because of geology, landform, soils, climate, biota, and human influences throughout the area.

Lichen: a symbiotic relationship between a fungus and an algae or cyanobacterium (Belnap *et al.*, 2001b).

LIM100m: Line-Intercept Method 100 m

LIM100m-whole line: Line-Intercept Method with a 100 m whole line that was used to measure BSC components.

Line-intercept method: the line-intercept method consists of horizontal, linear measurement

of plant intercepts along the course of a line. It is designed for measuring grass or grass-like plants, forbs, shrubs, and trees, to calculate or estimate frequency, density and cover.

Litter: The uppermost layer of organic debris on the soil surface, essentially the freshly fallen or slightly decomposed vegetal material (Society for Range Management, 1999). In this document, it includes persistent and non-persistent organic matter that is in contact with the soil surface.

Liverwort: A small, non-vascular plant (Belnap *et al.*, 2001b).

LPIM100m: Line Point Intercept Method 100 m

MGA 94: Map Grid of Australia, coupled with GDA 1994 datum

MFC: Middleback Field Centre

MIR: Mid InfraRed

MODIS: MODerate Resolution Imaging Spectroradiometer

Monitoring: the process of repetitive observing, for defined purposes, of one or more elements of the environment according to prearranged schedules in space and time using comparable methods for environmental sensing and data collection" (Meijers, 1986).

Morphological groups: are groups of superficially similar species that are difficult to differentiate in the field, but which possess similar morphologies and often function similarly e. g. " green leafy lichens" or gelatinous lichens" (Rosentreter & Eldridge, 2002).

MSS: MultiSpectral Scanner is a multispectral scanning radiometer that was carried on board Landsat 1, 2, 3 and 4.

Multispectral: colour images, can incorporate data from the visible spectrum, or from many parts of the visible, infrared and ultraviolet spectrum.

Nadir: the area on the ground directly beneath a scanner's detectors (Leica Geosystems, 2004a).

Nanometre (nm): Unit of distance equivalent to 10^{-9}m

NASA: National Aeronautics and Space Administration

NDVI: Normalized Difference Vegetation Index

Near-infrared (NIR): See infrared

Nitrogen fixation (fixers): The biological reduction of molecular nitrogen to chemical forms that can be used by organisms in the synthesis of organic molecules.

NOAA: National Oceanic and Atmospheric Administration

Non-vascular plants: plants without an internal vascular system of vessels for conducting water and nutrients from one part of their body to another. These plants lack true leaves and roots. For example, lichens, mosses, liverworts, fungi, algae.

Nutrient cycle: the cycle of nutrients such as nitrogen and phosphorus through the physical and biotic components of the environment; one of the ecological processes.

Panchromatic: black and white imagery based on the visible light spectrum

PCA: Principal Component Analysis

Pheno-phase: physiological stage of development in plants (Weber, 2001)

Perennial plant: a plant that continues to grow year after year at least more than 3 years (USDA 1997).

PD54: Perpendicular vegetation index (commonly called PD54)

PVI: Perpendicular Vegetation Index

QM10p: Quadrat Method with 10 (25 × 25 cm) plots

Radiance is the radiant intensity emitted (or scattered) by a unit area of source (surface)/ Unit: W m^{-2} sr^{-1} (ASD, 1999).

Rectification: the process of geometrically aligning two or more sets of image data such that resolution cells for a single ground area can be digitally or visually superimposed (Jensen, 1996).

Red edge: the red edge is defined as the point of maximum rate of change of the slope of the reflectance curve in visible red region (O'Neill, 1994b).

Reflectance: the ratio of the flux reflected by a surface to the incident flux (PP Systems, 1999).

Registration: making one image conform or fit another image.

Root mean square error (RMS): is the error term used to determine the accuracy of the transformation from one coordinate system to another. It is the difference between the desired output coordinate for a GCP and the actual (Jensen, 1996).

Sample size: the number of items or observations in a sample; usually denoted by lower case letter "n".

Sampling unit: a sampling unit is one of a set of objects in a sample that is drawn to make inferences about a population of those same objects. A collection of sampling units is a sample. Sampling units can be individual plants, points, plots, quadrats, or transects (BLM, 1999).

SAVI: Soil Adjusted Vegetation Index.

Sensor: a sensor is a device that gathers energy, converts it to a signal, and presents it in a form suitable for obtaining information about the environment (Colwell, 1983).

Shrub: a woody, perennial plant differing from a perennial herb in its persistent and woody stem, and less definitely from a tree in its lower stature and the general absence of a well-defined main stem.

Spatial enhancement: the process of modifying the values of pixels in an image relative to the pixels that surround them (Leica Geosystems, 2004a).

Spatial resolution: a measure of the smallest object that can be resolved by the sensor, or the area on the ground represented by each pixel (Leica Geosystems, 2004a).

Spectral analysis: study of data with respect to different spectral responses

Spectral bandwidth: is synonymous with spectral sampling interval (ASD, 1999).

Spectral reflectance: reflectance of electromagnetic energy at specified wavelength intervals.

Spectral resolution can be defined as the measure of the narrowest spectral feature that can be resolved by the spectrometer and can be characterized by the full width at half maximum of an instrument's response to a signal (van Aardt, 2000).

Spectral sensitivity: response, or sensitivity, of a film or detector to radiation in different spectral regions (NASA, 2004).

Spectral sampling interval: is the interval between data points in wavelength units (van Aardt, 2000). The "spectral sampling interval" is generally smaller than the spectral resolution.

Spectral signature: quantitative measurement of the properties of an object at one or several wavelength intervals.

Spectral vegetation index: an index of relative amount and vigor of vegetation. The index can be calculated from two or more spectral bands of a given remotely-sensed data (NASA, 2004).

Spectrometer: device for measuring intensity of radiation absorbed or reflected by a materiel as a function of wavelength (NASA, 2004).

Soil texture: the relative proportions of the various soil separates, primarily sand, clay, and silt. Subdivisions of the three basic separates, such as very fine sand, are often used.

Species composition: the proportions of various plant species in relation to the total on a given area. It may be expressed in terms of cover, density, weight, etc (Society for Range Management, 1999).

SPOT: Satellite Probatoire d'Observation de la Terre

Squamulose lichens: lichens that occur as discrete flakes or scales that are often rounded or ear shaped. Squamulose lichens may be convex or concave and often have lobed margins (Belnap *et al.*, 2001b).

SR: Simple Ratio

SSI: Soil Stability Index

Summer annuals: a species which germinates and completes its life cycle during the summer and early autumn months (Went, 1948).

SWIR: Short Wave InfraRed

Symbiotic relationship: refers to the intimate relationship between two organisms (Eldridge & Tozer, 1997b).

Temporal resolution: the frequency with which a sensor obtains imagery of a particular area (Leica Geosystems, 2004a).

Thallus: a more or less flattened vegetative plant/lichen body, without differentiation into stems and leaves (Eldridge & Tozer, 1997b).

Thresholds: It is the boundary in space and time between two states, for example grassland and shrub-invaded grassland; and the initial shift across the boundary is not reversible on a practical time scale without substantial intervention by the range manager (Friedel, 1991).

TM: Thematic Mapper is a multispectral scanning radiometer that was carried on board Landsats 4 and 5.

TNDVI: Transformed Normalized Difference Vegetation Index

TIN: Triangular Irregular Network

Universal Transverse Mercator (UTM) projection: a worldwide grid system of rectangular map coordinates that use metric units.

USA: United States of America

Vascular plants: plants with an internal vascular system of vessels for conducting sap between their roots and leaves. For example, trees, shrubs, herbs.

Virtual verification: can be done by examining the remote sensing data directly: there is sufficient spatial and / or spectral resolution to positively identify objects in the image (King & Clark, 2000).

Visible radiation: region of the electromagnetic spectrum that is visible to the human eye (approximately 400-700 nm). Often classified into the blue (400-500 nm), green (500-600 nm) and red (600-700 nm) (PP Systems, 1999).

WA: Western Australia

Waveband: User-defined region of the spectrum.

Wavelength: Distance between successive wave crests (troughs) or other equivalent points in a harmonic wave (PP Systems, 1999).

Winter annuals: a species which germinates and completes its life cycle during the winter and spring months (Went, 1948).

Zenith angle: angle measured from vertical to the position of an object. Zenith angle is 90° - elevation angle (in degrees).

ABSTRACT

This thesis considers various aspects of the use of ground-based methods and remote sensing of Biological Soil Crusts (BSC). They are mostly distributed in winter rainfall dominated areas such as those at Middleback Field Centre (MFC) in South Australia. They can be used potentially as an indicator of rangeland condition by estimating grazing pressure (trampling).

Two BSC based indicators for rangeland condition assessment are species composition and cover. While there is strong agreement that BSC composition is a good indicator, there is less agreement that BSC cover alone is a good indicator. Although BSC have been included in previous remotely-sensed studies, their spectral characteristics, and hence their contributions to remotely-sensed spectral signatures, are not well known.

Data collection methods were refined for suitable method selection, stratification and site characterization, and morphological/ functional group classification. Cover data of BSC were collected using a 100 m line-intercept method on the stratified land units and statistical analyses were based on the cover variance analyses. Spectra of BSC groups were collected and characterized for different remote sensing indices. Five grazing gradient models based on collected spectra were developed for the evaluation of BSC effect on remotely-sensed data. Both existing and newly developed remote sensing indices were examined for BSC detection.

Sampling for cover of BSC in the field showed that there is indeed a detectable change with distance from water, suggesting that BSC cover can be used as an indicator of rangeland condition, provided that appropriate stratification of the study sites is carried out prior to sampling, and spectral differences in morphological and functional groups are taken into account.

Spectral analysis of BSC components showed that different classes of organisms in the crusts have different spectral characteristics, and in particular, that the (commonly-used) perpendicular vegetation index (PD54) is not suitable for detecting BSC. On the other hand, ground-level spectral modelling showed that the Normalized Difference Vegetation Index (NDVI) and Soil Stability Index (SSI) did show a distinguishable contribution from BSC.

A procedure for detecting cover of BSC was developed for image taken during the period after an effective rain, in contrast to the normal practice of selecting images of dry surfaces for interpretation.

The most suitable intervals appears to be 2-4 days after rain in late autumn, winter and early spring. Of the existing indices, the SSI is the best for estimating cover of BSC from Landsat images. However, eight new indices, specifically designed for detection of BSC were

developed during the cource of this work. The best results were obtained for indices using using the middle-infrared bands.

These results are promising for application to rangeland monitoring and suggest that BSC cover is an important indicator of rangeland condition if appropriate stratification, classification and data-collection methods are used. The effects of BSC cover on a remotely-sensed method are considerable, and thus they can not be neglected during image interpretation. There are different phenological patterns for BSC, annual and perennial elements, thus there is the possibility for the selection of imagery based on each phenological stage to detect these elements. Application of certain indices such as the PD54 may create mis-estimation of land covers. Although some of the existing and newly developed indices had significant results for BSC cover estimation, there is a requirement for a standalone remotely-sensed method to conclude the best index.

DECLARATION

I declare that this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge it does not contain any materials previously published or written by another person except where due reference is made in the text.

Ardavan Ghorbani Date

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CHAPTER 1

1. GENERAL INTRODUCTION

1-1. Introduction

Rangeland ecosystems are complex and many variables simultaneously interact to produce the present state of these natural systems. They are important for supporting livestock and wildlife, and their role in soil and water conservation. A particular objective in natural rangeland monitoring— either in ground-based or in remotely-sensed methods—is having reliable results. Considering the limitations (cost / time) of ground-based methods and the capability of remotely-sensed data to rapidly provide accurate results for the whole surface of the rangeland, it would appear that remotely-sensed methods have advantages over ground-based methods (Poulton, 1975; Tueller, 1989; Bastin *et al.*, 1993a; Pickup *et al.*, 1994; Tueller, 1995). The use of remotely-sensed methods in rangeland assessment should provide more reliable results if the key ecological factors (e.g. soil, vegetation and rainfall) are simultaneously addressed. Remotely-sensed studies have mostly focused on vascular plant cover as the main indicator in rangeland condition assessment (Bastin *et al.*, 1993a; Pickup *et al.*, 1993; Pickup *et al.*, 1994; Pickup & Chewings, 1994; Washington-Allen *et al.*, 2004). A robust monitoring method has to use as many indicators as possible (Pyke *et al.*, 2002). In a few cases soil components have been considered in addition to vegetation components (Robinove *et al.*, 1981; Frank, 1984; Pickup, 1988; Pickup & Chewings, 1988b; Washington-Allen *et al.*, 2003). One of the rangeland condition indicators is Biological Soil Crusts (BSC) (Rogers & Lange, 1971; Klopatek, 1992; Eldridge & Koen, 1998). BSC composition is a good indicator and is well developed in ground-based methods (Rogers & Lange, 1971; Andrew & Lange, 1986a; Eldridge & Koen, 1998), however there is no strong agreement that BSC cover is a reliable indicator (Eldridge & Koen, 1998; Rosentreter & Eldridge, 2002). In spite of the BSC distribution in the world, including Australia, there has been little consideration given to monitoring these components using remotely-sensed methods (Karnieli *et al.*, 2001). Therefore, this research firstly aims to investigate BSC cover variance using ground-based methods. In a second stage, remote sensing of BSC is considered.

This chapter briefly outlines: the importance of rangeland; important background literature and a problem statement; current methods of rangeland condition monitoring; possible indicators for this purpose; and frameworks such as grazing pressure; piosphere (grazing gradient); ground-based data collection methods for cover variance analysis;

stratification and site characterization, and morphological / functional groups classification. Moreover, remote sensing of BSC is outlined. Finally, research questions, study area, spatial data and thesis structure are described.

1-2. Importance of Rangelands

Besides supporting livestock enterprises, rangelands have a significant role in soil and water conservation, wildlife habitat, catchment management and firewood for fuel (Grice & Hodgkinson, 2002). Natural grazing lands provide almost 75% of domestic animals' forage needs, while wildlife obtain a greater percentage of their needs from this resource (Williams *et al.*, 1968). Rangelands occupy large parts of Australia, and although most areas have low economic value, their total size means they cannot be ignored in an audit of Australia's land and water resources (Pickup *et al.*, 2001). In Australia nearly 3.44 million km^2 (58% of the arid area) is used for extensive pastoralism, grazing by sheep or cattle (Pickup *et al.*, 2001). Overall, the approximate monetary benefit in Australia has been estimated to be $19.6 billion per annum (Table 1-1).

Table 1-1. Australia's rangeland annual income adapted from NLWRA (2001)

Relative Industry	Benefits (billion) $
Mining	12.0
Cattle & beef	4.4
Tourism	2.1
Sheep and wool	1.1
Total	**19.6**

1-3. Rangeland Degradation and Its Effects

Given the importance of rangeland ecosystems, they are at risk through inappropriate practices leading to degradation. Rangeland degradation, due to intensified use and mismanagement, is occurring worldwide in arid and semi-arid regions. This has attracted the attention of the international community, mobilizing scientists and also policy makers at a very high level, leading to international efforts to combat degradation (Pickup, 1989; Kassas, 1995). It is in everyone's interest to reduce the rate of land degradation by improving management practices.

Rangeland degradation can be characterized in terms of accelerated soil erosion, a change in soil quality and change in biological components (Newman & Condon, 1969; Pickup, 1989; Bastin *et al.*, 1993a; Brook *et al.*, 2001; Tongway *et al.*, 2003). Degradation, loss of productivity potential, and biodiversity decline on the rangelands of Australia have

resulted from inappropriate grazing practices over 150 years (Brook *et al.*, 2001). Brook *et al.* (2001) stated that past grazing practices have lacked flexibility to cope with a dynamic landscape that fluctuates according to rainfall events. During dry periods, the large number of livestock concentrated around permanent watering points has resulted in high grazing pressure and trampling of vegetation leading to soil disturbance, erosion and a redistribution of water and nutrients across the landscape (Andrew & Lange, 1986a, b; Pickup *et al.*, 1993; Pickup *et al.*, 1994). The breakdown of essential ecological processes (landscape function) results in a decline of the productive potential of the landscape with some areas failing to respond to subsequent rainfall events (Brook *et al.*, 2001).

Rangeland degradation in particular causes significant ecosystem problems such as the reduction of soil stability and productivity, and also changes in biodiversity and hydrological functions (Pickup, 1989; Bastin *et al.*, 1993a; Tongway *et al.*, 2003). The major cause of rangeland degradation has been identified as an increase in the number of livestock and overgrazing (FAO, 2002). From 1950 to 2001, the number of grazing animals worldwide has almost doubled (Earth Policy Institute, 2002). Because of this increase, soil and water conservation, grazing capacity and rangeland productivity have decreased during this period. The approximate monetary loss caused by rangeland degradation worldwide has been estimated to be US$23,334 million per annum, while in Australia it is US$2,529 million per year (Dregne *et al.*, 1991; Kassas, 1995). Rangeland degradation in Australia, including South Australia, has been identified and addressed by several studies and government reports (Newman & Condon, 1969; Dregne, 1983; Harrington *et al.*, 1984; Woods, 1984; Christie, 1986; Foran, 1987; Pickup, 1989; Bastin *et al.*, 1993a; Pickup, 1998; Brook *et al.*, 2001; Friedel *et al.*, 2003; Tongway *et al.*, 2003). According to this extensive literature, rangeland degradation in Australia is often considered to be both the result of human behaviour and natural hazards; e.g. drought and fire. Many studies have been conducted since the 1980s, but it is important that there are continuing studies which utilize methods sensitive to the discrimination of rangeland degradation in its early stages and which critically assess rangeland management practices.

1-4. Monitoring of Rangeland Conditions

One preliminary step in identifying and preventing degradation can be the evaluation and monitoring of rangeland condition. Monitoring to define the extent of degradation has been identified as one of the important, difficult, time consuming and contentious issues in rangeland management (Bastin *et al.*, 1993a). Until the 1980s, rangeland monitoring relied on visual air photo interpretation and ground-based methods (Poulton, 1975; Paine, 1981;

Tueller, 1989; Bastin *et al.*, 1993a). Remote sensing technologies have had great impact on the development of new methods in rangeland evaluation and subsequently in other areas of renewable resources management. Thus, for rangeland condition assessment, two groups of methods are used to monitor and quantify the level of degradation. First traditional ground-based or the group of methods which are based on visual interpretation of aerial photographs and ground data collection (Poulton, 1975; Paine, 1981; Bonham, 1989); and second, remotely-sensed methods that are based on digital image processing combined with ground verification (Pickup & Nelson, 1984; Bastin *et al.*, 1993a; Pickup & Chewings, 1994; Bastin *et al.*, 1998). Literature has reported that remotely-sensed methods have advantages, such as the ability to monitor larger areas with repeatability potential, over ground-based methods (Poulton, 1975; Tueller, 1989; Bastin *et al.*, 1993a; Pickup & Chewings, 1994; Tueller, 1995) (See Chapter 2).

1-5. Indicators in Ground-based and Remotely-sensed Methods of Rangeland Condition

Rangeland condition assessment in ground-based and remotely-sensed methods is based on the monitoring of biophysical indicators to evaluate the level of land degradation. Using different indicators to discriminate rangeland condition is well established in ground-based methods (Pickup, 1985, 1989; Tongway, 1995a; Herrick *et al.*, 2002; Pyke *et al.*, 2002). However, previous studies have reported that there are substantial limitations such as the time, labour and costs required to conduct ground-based methods in assessing rangeland condition (Bastin *et al.*, 1993a; Brook *et al.*, 2001). By contrast, many studies have reported that rangeland assessment based on remotely-sensed methods can provide highly effective and efficient monitoring from repetitive and consistent reflectance data over large areas (Graetz & Pech, 1987; Pickup & Chewings, 1988b, a; Pickup, 1989; Bastin *et al.*, 1993a; Pickup *et al.*, 1993; Bastin *et al.*, 1998). However, remotely-sensed methods, because of the limitations in detecting various features (i.e. soil, micro-organisms and non-photosynthetic features), have usually focused on a limited set of indicators. Thus, a reliable method of rangeland condition assessment may combine the potential of both ground-based and remotely-sensed methods to use more indicators, thus leading to more robust results (USDA/JERP, 2003).

1-6. Biological Soil Crusts as an Indicator of Rangeland Condition

One of these possible indicators is BSC. BSC are a complex mosaic of cyanobacteria (blue-green algae), eukaryotic green algae, lichens, mosses, microfungi, and other bacteria (West,

1990; Belnap *et al.*, 2001a). They have strong influence on soil stability and soil conservation (Tongway & Smith, 1989; Klopatek, 1992; Eldridge & Koen, 1998; Belnap *et al.*, 2001b). BSC perform many important ecological functions including: fixing atmospheric nitrogen (Shields, 1957; Belnap, 1994); improving plant, soil and water relationships (Lange *et al.*, 1986; Eldridge, 2000); contributing to nutrient cycling (Shields, 1957; Skujins, 1984); providing sites for seed germination and plant growth; and, altering soil factors including water availability, nutrient content and erosion susceptibility (Eldridge & Westoby, 1991; Klopatek, 1992; Eldridge & Koen, 1998; Belnap *et al.*, 2001c). BSC are particularly sensitive to ground disturbance, especially compression caused by animal or human foot and vehicular traffic (Eldridge & Tozer, 1997b; Belnap, 1998). Thus, it is probable that pastoralism has an impact on BSC which in turn affects many other resources and environmental factors, including soil stability, water quality, nutrient cycling, and in turn the vegetation and other organisms they support (Filson & Rogers, 1979; Belnap *et al.*, 2001b; Belnap & Lange, 2001).

1-7. BSC Monitoring Using Ground-Based Methods

While there has been increased attention to the ground-based monitoring of BSC (Tongway & Smith, 1989; Klopatek, 1992; Eldridge & Koen, 1998; Belnap *et al.*, 2001b), there is no clear methodology for their cover analysis and no agreement about the importance of them as an indicator (Klopatek, 1992; Eldridge & Koen, 1998). Early efforts to evaluate soil surfaces including BSC were developed in the semi-arid woodlands of eastern Australia (Tongway & Smith, 1989). This assessment showed differences in the stability, erosion, and nutrient status of soil surfaces and provided a reliable estimate of potential productivity of the surface independent of vascular plants. This system was later refined and extended to other landscape types and included other soil characteristics, such as the degree of cracking, surface coherence, and micro-topography (Eldridge & Koen, 1998; Holm *et al.*, 2002). In New South Wales the Department of Land and Water Conservation has been collecting data (including BSC cover) on the condition and trend of rangelands since the mid-1980s (Green, 1992). Similar US studies collecting cover estimates for BSC since 1987 (Pellant, 1996; Belnap *et al.*, 2001b). These studies have mostly used standard or slightly modified rangeland assessment techniques (Belnap *et al.*, 2001b; Rosentreter *et al.*, 2001). In Australia small size quadrats are mostly used (Rogers, 1970; Rogers & Lange, 1971; Eldridge, 1996a; Eldridge, 1999), while in the USA quadrat and line-intercept methods are common (Kaltenecker, 1997; Ponzetti *et al.*, 1998).

1-8. Grazing Pressure (Trampling) as a Framework

For rangeland condition monitoring using indicators some frameworks such as grazing pressure are identified. Grazing intensity or trampling pressure is a fundamental problem in the management of rangeland. It reduces the production of forage; exposes the soil to sealing, baking, trampling and erosion; reduces the infiltration of water into soil; increases water run off and flooding; and, induces unfavourable changes in the species composition of the native vegetation (Heshmatti, 1997). Grazing also influences attributes of plant communities such as species composition, biomass and plant architecture (Manseau *et al.*, 1996). It affects foraging areas by defoliating plants and trampling soil (Matches, 1992) leading to the reduction of macropore space and infiltration, percolation, root growth, soil surface micro-organisms and overall plant production (Bryant *et al.*, 1972). Klopatek (1992) reported that BSC are highly responsive indicators of trampling. The amount of degradation can be judged using biodiversity and cover of BSC (Rogers & Lange, 1971; Klopatek, 1992; Eldridge & Koen, 1998).

1-9. Piosphere as a Framework

The level of degradation under grazing pressure (trampling) needs to be assessed within a sensitive framework. Drinking water is the key to activities of stock in arid and semi-arid environments world-wide and results in an intensive zone of influence around a water point which decreases with distance from the water (Squires, 1982). As well as grazing effects, there are also effects from trampling and dust associated with the movement of animals close to the water point (Andrew & Lange, 1986a). This impact is termed "piosphere" in ground-based (Lange, 1969; Andrew & Lange, 1986a, b; Andrew, 1988) and "grazing gradient" in remotely-sensed studies (Bastin *et al.*, 1993a; Pickup *et al.*, 1994; Pickup & Chewings, 1994; Washington-Allen *et al.*, 2004). It is identified as a sensitive framework for grazing pressure (trampling) analysis and rangeland degradation assessments. Damage to soil crusts is most obvious close to watering points, but not all lichens are affected to the same degree (Rogers & Lange, 1971).

1-10. Ground-based Data Collection Methods

BSC are typically measured using standard or slightly modified rangeland assessment techniques (Belnap *et al.*, 2001b). Existing literature has introduced three ground-based methods including small size quadrats, line-intercept and point intercept methods (Belnap *et al.*, 2001b; Rosentreter *et al.*, 2001; Rosentreter & Eldridge, 2002). To my knowledge, apart

from Eldridge and Tozer's (1995) study there is little consideration for comparing methods suitable for BSC monitoring. It seems that most of the studies either followed typical rangeland assessment techniques reported in the literature or modified these slightly. This study aims to perform a small pilot study to determine a suitable method for BSC monitoring.

1-11. Stratification as a Framework

A number of studies have emphasized that stratification can improve spatial sample collection accuracy and grazing gradient results (Graetz & Ludwig, 1978; Ludwig & Tongway, 1992; Bastin *et al.*, 1993a; Bastin *et al.*, 1998; Wright *et al.*, 2003). Belnap *et al.* (2001b) have stated that stratification can improve BSC monitoring where the landscape is composed of a number of relatively homogeneous land units such as those at the Middleback Field Centre (MFC). Stratification for BSC monitoring has been used infrequently (Ludwig & Tongway, 1992). Bastin *et al.*(1998) and Brook *et al.* (2001) reported that heterogeneity in land systems or land units may override grazing gradients, thus causing bias in the results.

1-12. Morphological /Functional Groups as a Framework

BSC species are diverse (Büdel, 2001; Eldridge, 2001). Their identification presents problems due to their small size and the intermixing of species and their distribution in different ecological and geographical situations (Eldridge & Rosentreter, 1999). Using BSC as an indicator for rangeland monitoring requires identification of their constitute organisms or a classification of them based on their properties such as morphology or ecological function (Eldridge & Rosentreter, 1999). Some studies have been conducted to classify these organisms for ready use in different eco-regions (Eldridge & Koen, 1998; Eldridge & Rosentreter, 1999; Rosentreter *et al.*, 2001). Classifying BSC diversity in small homogeneous groups can facilitate ground data collection for ground-based and remotely-sensed methods.

1-13. Cover Variance Analysis

As reviewed in Section 1-1, there is no strong agreement that BSC cover alone is a good indicator of land degradation (Eldridge & Koen, 1998; Rosentreter & Eldridge, 2002). Although these studies have considered some pre-assessment issues such as morphological grouping, or seasonality pattern simulation using wetting, other issues such as resource stratification and sampling method selection have received less consideration. Cover is considered the best indicator of protection of the landscape against degradation (Bastin *et al.*,

1993a; Pickup & Chewings, 1994). It is one of the commonly measured attributes in vascular and non-vascular plant sampling for rangeland monitoring in ground-based and remotely-sensed methods (Bonham, 1989; Bastin *et al.*, 1993a; Pickup *et al.*, 1994; Pyke *et al.*, 2002).

1-14. The Need to Consider Phenology for Image Selection for BSC Monitoring

Historically, the term "phenology" has usually referred to specific agricultural events such as planting, emergence, fruiting and harvest (Reed *et al.*, 1994). However, this term has broadened to mean the study of periodic natural events e.g. emergence, growth and senescence of vascular plants, and the cause of their timing influenced by biotic and abiotic forces- especially temperature change driven by weather and climate, and the interaction among ecosystems of the same or different species (Lieth, 1974; Reed *et al.*, 1994; Schwartz, 2003). Some aspects of abiotic environmental factors—such as temperature variation and the rainfall regime—effect phenological patterns with consequential impacts on remote sensing imagery.

1-15. BSC Monitoring Using Remotely-sensed Methods

A holistic view of BSC disturbances and erosion using remotely-sensed approaches has not had a significant role in former BSC evaluations (Karnieli *et al.*, 2001). Some BSC components, particularly BSC growth after rainfall, have a specific spectral signature and should be considered when undertaking image processing (O'Neill, 1994b; Karnieli & Tsoar, 1995; Karnieli & Sarafis, 1996; Karnieli *et al.*, 2001; Karnieli, 2003; Chen *et al.*, 2005; Burgheimer *et al.*, 2006b; Burgheimer *et al.*, 2006a). Some research has identified BSC spectral characteristics using both field and laboratory analysis (O'Neill, 1994b; Karnieli & Tsoar, 1995; Pinker & Karnieli, 1995; Karnieli & Sarafis, 1996; Karnieli *et al.*, 1996; Karnieli *et al.*, 1997; Karnieli *et al.*, 1999; Karnieli *et al.*, 2001). Some claim that the spectra of dry BSC are similar to that of bare soil (Karnieli & Sarafis, 1996; Karnieli *et al.*, 1996; Karnieli *et al.*, 1999; Karnieli *et al.*, 2001), while others—to avoid moisture effects—have selected imagery when BSC were dry (Cameron & Lewis, 1996). However, only a few studies have used remote sensing for BSC mapping (Wessels & van Vuuren, 1986; Karnieli, 1997; Chen *et al.*, 2005). In some studies BSC cover was a part of multispectral and hyperspectral image processing (Perry, 1977; Bork *et al.*, 1998; Lewis *et al.*, 2001; Fildes, 2005). Overall, the effect of BSC spectra in image processing, particularly in Australia, has been hardly considered. It seems that most remotely-sensed studies were carried out under dry conditions

and have interpreted BSC as bare soil throughout the world (Karnieli *et al.*, 1996; Karnieli *et al.*, 2001; Karnieli, 2003).

Remotely-sensed data were usually selected by concentrating on a suitable period of annual and perennial growth after a significant rainfall on the rangeland areas in order to give the opportunity of plant growth leading to a high greenness index value. Vascular plant growth occurs several weeks after rain when surface moisture has reduced and thus this timing avoids soil moisture issues (Bastin *et al.*, 1993a; Pickup *et al.*, 1994; Pickup & Chewings, 1994; Cameron & Lewis, 1996). In the case of an area such as that at MFC which is characterized by winter-dominated rainfall where BSC are common (Rogers, 1972; Eldridge, 2001), the influence of BSC on the remote sensing has not been considered (Cameron & Lewis, 1996).

1-16. Spatial Dataset

Base spatial data of the study area such as digitized topographic maps including: Cultana, Ironbaron, Middleback, Randell, Roopena and Whyalla (1:50,000) (DEHAA, 1998); digital topographic dataset including surface hydrology data, elevation spot points and contour lines (DEHAA, 2004) and previously developed GIS layers such as water resources and paddock boundaries; (DEHAA, 2003) and Landsat Thematic Mapper (TM) imagery were the digital spatial datasets which were used in this thesis. All spatial data have registered to the Universal Transverse Mercator (UTM) map projection with a datum of the Geodetic Datum of Australia (GDA 94).

1-17. Research Questions

The aim of this thesis is to investigate both ground-based and remotely-sensed methods for detecting and discriminating BSC in South Australia chenopod shrublands for rangeland condition assessment. Specific questions of the study for ground-based and remote sensing of BSC are:

1-17-1. Ground-based Assessment of BSC

Q1. Is there a spatial change in the cover of BSC related to trampling (grazing pressure) that could be used as an indicator of rangeland condition?

In the framework of piosphere only the trend of BSC cover change (variance) was planned to be considered as:

1. Does BSC cover change significantly in the framework of the piosphere?

1-17-2. Remote Sensing of BSC

Q2. What are the BSC spectral characteristics in dry and wet conditions in comparison with other land covers?

Particularly, the project aims were to evaluate whether significant differences exist between the spectral signatures of BSC and other major land cover types such as vascular plants, bare soil, litter and shadow, with different amounts of moisture and at different times of the year. Spectral characteristics were considered in more detail in the following sub-questions:

1. What are the spectral characteristics which may assist in the detection of BSC?
2. What are the effects of dry and wet BSC on the indices-based remotely-sensed methods such as the perpendicular vegetation index (commonly called PD54) and Soil Stability Index (SSI)?

Q3. What are the effects of BSC on the spectral patterns of grazing gradients?

In order to understand how BSC spectra affect the cover estimation of rangeland features in dry and wet conditions, sub-questions are:

1. What are the index value differences for varying BSC in dry and wet conditions?
2. What are the index value differences between BSC and other rangeland features in dry and wet conditions?
3. What are the differences between surfaces (plot) covered with BSC and bare ground by ground-level spectral analyses?
4. What are the possible models based on the ground-level spectra to evaluate grazing gradient patterns with and without BSC?
5. What is the temporal change in spectra as a function of changes in the moisture?

Q4. What is the possibility of using multispectral datasets for detecting BSC?

Remote sensing of BSC in more detail is considered in the following sub-questions:

1. What are the most appropriate times for image selection for BSC detection?
2. Is it possible to detect BSC as one of the important land covers using existing or new indices derived from multispectral remote sensing?

1-18. The Study Area

The study area is Middleback Field Centre (MFC) in the pastoral region of the South Australian chenopod shrublands (Figure 1-1) in the south-east Gawler Ranges bioregion (GRSCB, 1996), approximately 400 km north-west of Adelaide. BSC is one components of

rangelands at MFC (Rogers, 1970; Rogers & Lange, 1971; Howarth, 1983; Eldridge, 2001). The study paddocks are further described in Section 3-3.

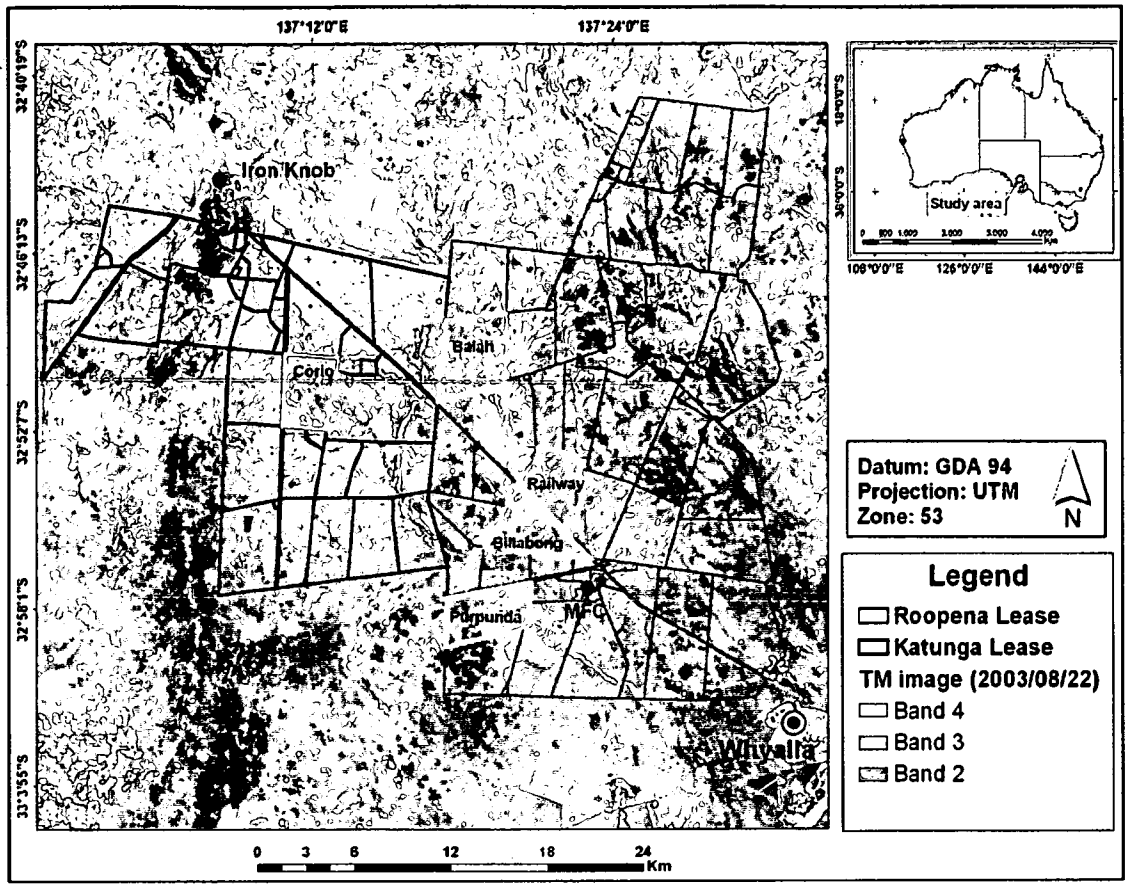

Figure 1-1. The study area, MFC and study paddocks, 20 km north-west of Whyalla, South Australia

1-19. Thesis Outline

The general hierarchical plan of this thesis is shown in Figure 1-2. Chapter 1 introduces rangeland monitoring approaches and frameworks to investigate the use of BSC cover as an indicator of rangeland condition. The second chapter reviews theories and research on rangelands, their monitoring and BSC, with specific references to Australia including South Australia. The chapter also outlines remote sensing theories and methods. Chapter 3 presents general background information and methods by considering paddock selection; suitable method selection; stratification for sample locations; distances and locations of samples; ground data collection; landscape and site characterization, and the process of classifying the morphological /functional groups for this study. Specific methods are included in individual chapters. Chapter 4 describes the land cover features and analyses of BSC cover variance under grazing pressure (trampling). Chapter 5 presents the spectral characterization of different rangeland covers including the morphological / functional groups in comparison with different land covers. Chapter 6 presents the grazing gradient models by ground-level

spectra to conceptualise the effects of BSC on the grazing gradient patterns. Chapter 7 focuses on the timing of remote sensing image selection, performs tests of existing remote sensing indices and develops new indices for BSC detection. Finally, Chapter 8 discusses the pre-assessment issues for BSC monitoring and cover analysis. It also discusses ground-level spectral characterization, ground-level spectral modelling, timing of image selection and image-based remote sensing of BSC.

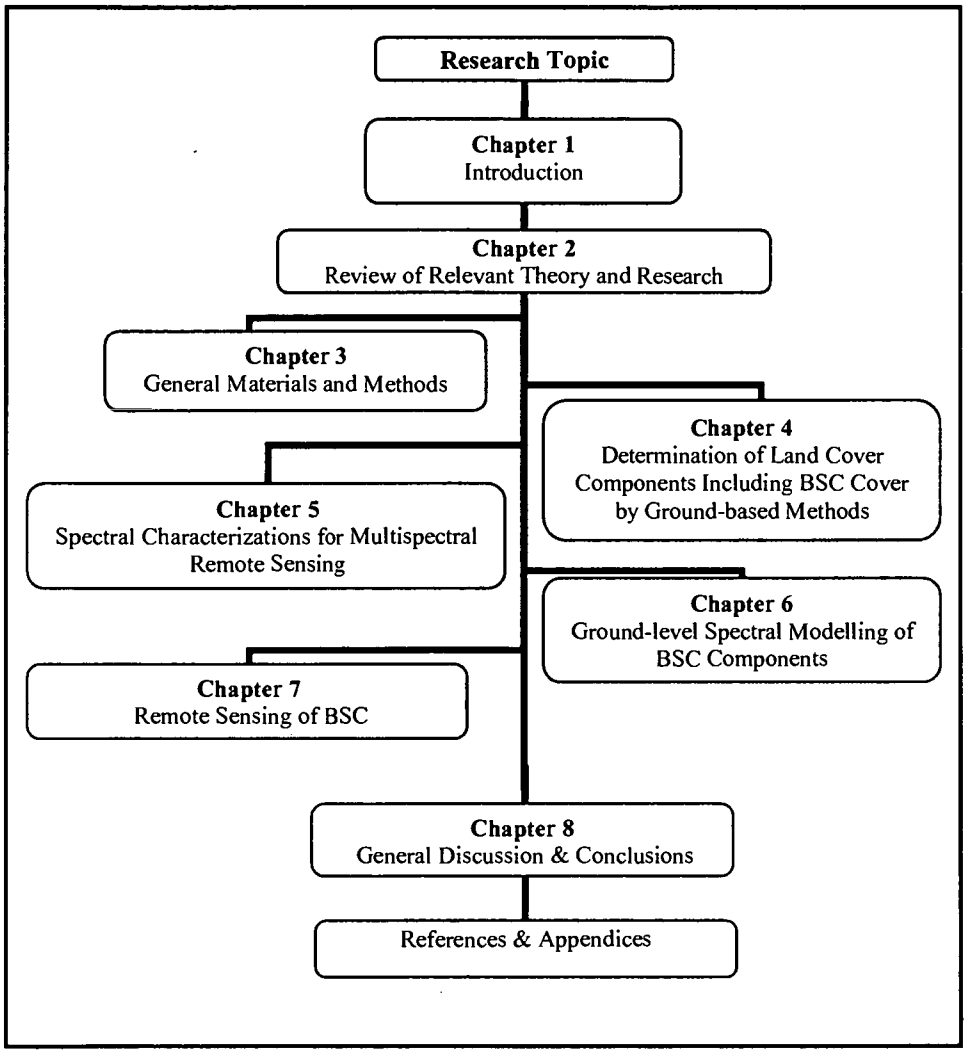

Figure 1-2. Schematic view of the thesis structure

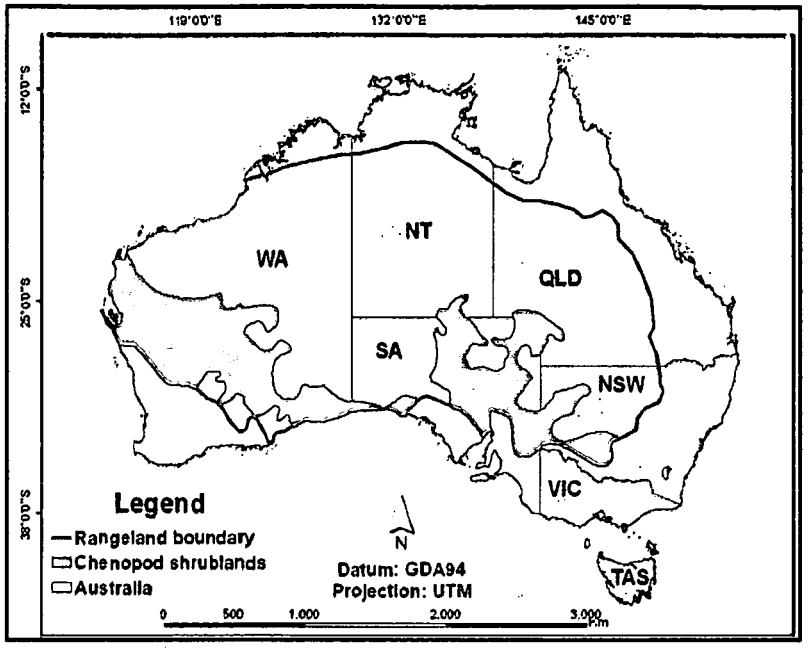

Figure 2-1. Arid and semi-arid rangelands and chenopod shrublands association distribution, adapted from Wilson and Graetz (1979)

2-3. Rangeland Degradation

Rangeland degradation takes place as a result of excessive numbers of livestock and unsuitable rangeland management (FAO/UNDP/UNEP, 1994). In addition, degradation reduces the diversity, amount and value of the products that rangelands provide, and severe rangeland degradation can be irreversible (NRC, 1994). Rangeland degradation is usually a human induced problem rather than a physical problem (Pickup, 1989) and arises when land use does not match land capability. Ungrazed rangelands are less affected although the impact of native and feral animals, and changed biodiversity from fire is thought to be significant in fire affected areas. Degradation cannot be identified and assessed without knowledge of the land use pattern and ecology (Pickup, 1989). Degradation can include the interaction of changes in the physical, chemical and biological properties of soil as well as changes in vegetation vigour; species composition; BSC disturbance; litter accumulation and distribution; seed germination and seedling recruitment; total biomass production, and other ecological functions (NRC, 1994; NRCS, 1997). Soil degradation can be classified as: chemical (e.g. comprising acidification, salinization and leaching) and physical degradation (e.g. comprising crusting, compaction, hard-setting and erosion). Some rangeland units are affected by more than one degradation process. Unless a clear distinction is made, there is a considerable chance of overlap and double accounting.

At the level of vegetation, rangeland degradation reduces grazing capacity (FAO/UNDP/UNEP, 1994) and changes in the plant species composition (Washington-Allen *et*

al., 2001). There may be an increase in low quality forage species compared with high quality forage, or a decrease in plant productivity (Washington-Allen *et al.*, 2001).

At the landscape level, Tongway *et al.* (2003) defines "... change in the manner in which scarce resources are redistributed in space and time". Land degradation causes a change in landscape structure and pattern that leads to detrimental changes in ecosystem function (Pickup, 1989). Bastin *et al.* (1993a) defines rangeland degradation in a more specific way as "... reduction in the capacity of landscapes to produce vegetation cover from rainfall".

2-3-1. Rangeland Degradation in South Australia

The extent and severity of land degradation in South Australian rangelands, as stated by some literature, (Ratcliffe, 1936; Landsberg *et al.*, 1997; Brook *et al.*, 2001; Gould *et al.*, 2001) is severe compared with other parts of Australia. In particular a severe drought from 1864 to 1869 combined with heavy grazing pressure destroyed much of the perennial saltbush in South Australia (Landsberg *et al.*, 1997). A government Commission (SA Government, 1867) into the state of the pastoral leases at the time summarized evidence of widespread death of saltbush, loss of 7-15 cm of topsoil, and massive stock losses (Landsberg *et al.*, 1997). By the 1930s, perennial shrubs had been severely depleted and carrying capacity of South Australian rangeland had decreased (Newman & Condon, 1969; Landsberg *et al.*, 1997).

2-4. Rangeland Condition

The term "rangeland condition" is an ecological term derived from the Clementsian idea of plant succession (Clements, 1916, 1920), which assumes predictable, linear and reversible changes in the vegetation and soil away from a climax situation, which is largely determined by climate and soil in response to grazing (CSIRO, 1998). It is also defined as a value-laden term, often associated with particular models of rangeland change or particular models of measurement (Friedel *et al.*, 2000). Sometimes, it is assumed to exist in some absolute form and assessments are designed to capture it, or at least to approximate it as closely as possible (Friedel *et al.*, 2000). The differences amongst definitions are significant, and reflect the perceptions of how and why change occurs under use, and the objectives of assessment. The current status of rangeland is often called rangeland condition, and is sometimes equated with health (NRC, 1994; Eldridge & Koen, 1998; Pyke *et al.*, 2002), in which there is no single measure of absolute condition but, rather, a series of indicators, not one of them sufficient on their own (NRC, 1994; NRCS, 1997; Friedel *et al.*, 2000; Pyke *et al.*, 2002).

2-4-1. Conceptual Models of Rangeland Condition

In order to decide how, what, when and where to measure, models are required of how rangelands change in response to use, even if the models are simply conceptual (Friedel, 1991; Friedel *et al.*, 2000). There are two general conceptual models of dynamic change in the literature related to rangeland, which have been proposed to evaluate rangeland change over time. The succession model proposed by Clements (1916), which was developed for rangeland classification by Sampson (1917; 1919), and rangeland condition assessment by Dyksterhuis (1949), which is based on an assumption of continuous change leading to a stable community. In the succession model all possible states of vegetation can be arrayed on a continuum and condition is the term for the vegetation's position on this continuum. Several studies have pointed out that the succession model does not fit observed community dynamics for many of the world's rangeland communities (Laycock, 1989; Smith, 1989; Westoby *et al.*, 1989; Laycock, 1991), particularly in the more arid rangeland systems. It may be that this model is more applicable to moist environments, while arid environments are better described by a more discontinuous model (Dankwerts & Adams, 1991; Laycock, 1994; Friedel *et al.*, 2000).

On the other hand, a new dynamic model of rangeland change was introduced by Westoby *et al.* (1989), which is based on discontinuous change and uses the concept of threshold (Friedel, 1991; Laycock, 1991). A threshold describes the boundary in space and time between two states, for example grassland and shrub-invaded grassland; and also demonstrates that the initial shift across the boundary is not necessarily reversible on a practical time scale without substantial intervention by the rangeland manager. State-and-transition model and threshold concepts were integrated by Laycock (1991) to interpret discontinuous change over time in rangeland areas. It seems that the state-and-transition model is more suitable for interpreting the discontinuous change of rangeland areas instead of regularly continuous changes (Hunt, 1992; Lockwood & Lockwood, 1993; Stringham *et al.*, 2003). In both models of rangeland condition the selection of suitable criteria and indicators of change are crucial.

2-4-2. Criteria of Assessment and Indicators of Rangeland Condition

The condition of a plant, animal community or site is frequently difficult to quantify (Breckenridge *et al.*, 1995). A method or system that assesses rangeland condition must be able to distinguish between changes that result in the crossing of a threshold from those that are temporary because of normal fluctuations in physical or biological factors (Friedel *et al.*, 2000). Ellison (1949) noted the difficulty of monitoring ecosystems using only one indicator. Indicators, particularly ecological ones, are widely used to measure the condition or health status of ecosystems. A suite of indicators to assess ecosystem conditions has been used by many

researchers (Odum, 1985; Rapport *et al.*, 1985), while some (Bastin *et al.*, 1993a; Bastin *et al.*, 1993b; Pickup *et al.*, 1993) have focused on one particular indicator (vegetation cover change). Most environmental indicators are used as substitutes to assess stressors in ecosystems (Andreasen *et al.*, 2001). Ecological systems are composed of complex biological, chemical and physical components that are difficult to understand and to measure. However, effective management actions and policy decisions require information on the status, condition and trend of ecosystems (NRC, 1994). Research on the use of indicators has found that a relatively small number of ecosystem level indicators are sufficient to represent ecological health (Rapport *et al.*, 1981).

2-5. Biological Soil Crusts

2-5-1. Definitions and Terms

BSC are defined in Section 1-6. They have also been known as microfloral (Loope & Gifford, 1972), cryptogammic (Kleiner & Harper, 1972), biological (Danin, 1978), organogenic (Evenari, 1985), biocrusts or biogenic (Thomas & Tsoar, 1990), microphytic (Cameron, 1978), biotic (McCune, 1992), microbiotic (Belnap, 1990), cryptobiotic (Belnap, 1993) and cryptogamic (St. Clair & Johansen, 1993) crusts. However, the most recently and widely recognised term used in the world is Biological Soil Crusts (BSC) (Eldridge, 1998a; Belnap, 2001; Eldridge, 2001; Belnap, 2002; Belnap, 2003; Bowker *et al.*, 2004; Belnap *et al.*, 2006). BSC live within, or immediately on top of, the uppermost 50 mm of soil (Belnap *et al.*, 2001a). They have been described as biological filaments that weave through the top few millimetre of soil, gluing loose particles together and forming a matrix that stabilizes and protects soil surfaces from erosive forces (Cameron, 1966; Belnap *et al.*, 2001b). They contribute to the biodiversity of arid systems (West, 1990). Distinction should be made between physical, chemical and biological crust formations (Williams, 1994). Physical crust is defined either as one formed by a combination of raindrop impact on the soil surface along with physiochemical dispersion of soil clay, or as one formed by the sedimentation of fine material as turbid water infiltrates following overland flow (Singer, 1991). Chemical crust is defined as salt crusts, gypsum crusts, or silica crusts, which often occur in association with biological crusts (Williams, 1994). Thus, biological crusts are distinguishable from crusts formed by chemical or physical processes (West, 1990). The current study, by considering literature (Rogers, 1970; Rogers & Lange, 1971; Andrew & Lange, 1986a) and reconnaissance field visits, investigates the soil-based biological crusts for rangeland condition assessment.

2-5-2. Habitat Distribution of BSC

Biological crusts are common in habitats where water and nutrients tend to be limited and vascular plant cover is discontinuous. They can develop on different substrata such as rocky materials (e.g. limestone, chalk, dolomite, sandstones and granite), as well as on different soil types such as loess and dune sand (West, 1990; Belnap, 1993). They are able to exist in extreme environmental conditions, surviving through extended periods of desiccation and extreme high and low temperatures (Lange, 1990). Some of these can be sustained or re-established by hydration from fog, dew, or simply high vapour pressure (Lange & Tenhunen, 1982; Lange *et al.*, 1990). These types of organisms are referred to as poikilohydric (Burgheimer *et al.*, 2006a). The moisture content threshold to regain activity is different for the various taxa that contribute to the biological crusts and results in a certain distribution pattern (Lange *et al.*, 1997; Lange, 2001). BSC exist in all climates and regions. Roughly, mosses seem to favour the comparatively more mesic sites (200–300 mm of rain), lichens dominate intermediate sites (100–200 mm), and cyanobacteria favour the harshest sites (less than 100 mm) (Burgheimer *et al.*, 2006b). In these ecosystems they can cover up to 100% of an area (West, 1990; Belnap, 1993; O'Neill, 1994a; Fildes, 2005; Belnap *et al.*, 2006). According to Howarth's (1983) study, soil factors, particularly clay content, pH, local variations in rainfall, soil surface condition, soil nutrition and erosion, influence the distribution of mosses at a microsite scale.

2-5-3. Distribution of BSC in the World

BSC being non-vascular, have a limited ability to grow upwards from the soil surface and are therefore generally unable to compete with vascular plants for light (Belnap *et al.*, 2001a). Consequently, they are well developed on the soil surface in the interspaces of open shrubland, grassland and woodland communities of arid, semi-arid and arctic ecosystems where micro-climatic conditions permit them to develop in the interspaces (Harper & Marble, 1988; Klopatek, 1992; Belnap *et al.*, 2001a; Belnap *et al.*, 2001b).

2-5-4. BSC in Australia

BSC and their constituent organisms are common components of landscapes in semi-arid and arid Australia (Rogers, 1982; Eldridge, 2001). They are generally restricted to rangelands (Figures 2-1 & 2-2) (Eldridge, 2001). The soils in these areas are exceptionally old, and are generally shallow, infertile, and highly weathered (Eldridge, 2001). Unpredictable rainfall in this area (Stafford Smith & Morton, 1990; Bastin *et al.*, 1993a) has an overriding influence on the functioning of ecosystems (Eldridge, 2001). Many landscapes react to low rainfall by being strongly patterned into discrete soil and vegetation patches at a range of spatial scales (Ludwig *et*

al., 1997; Ludwig *et al.*, 2004). Micro-organism diversity is greatest within patches that receive extra resources (run on zones or fertile patches), and these patches ultimately become refugia for plants and animals during unfavourable times (Eldridge, 2001).

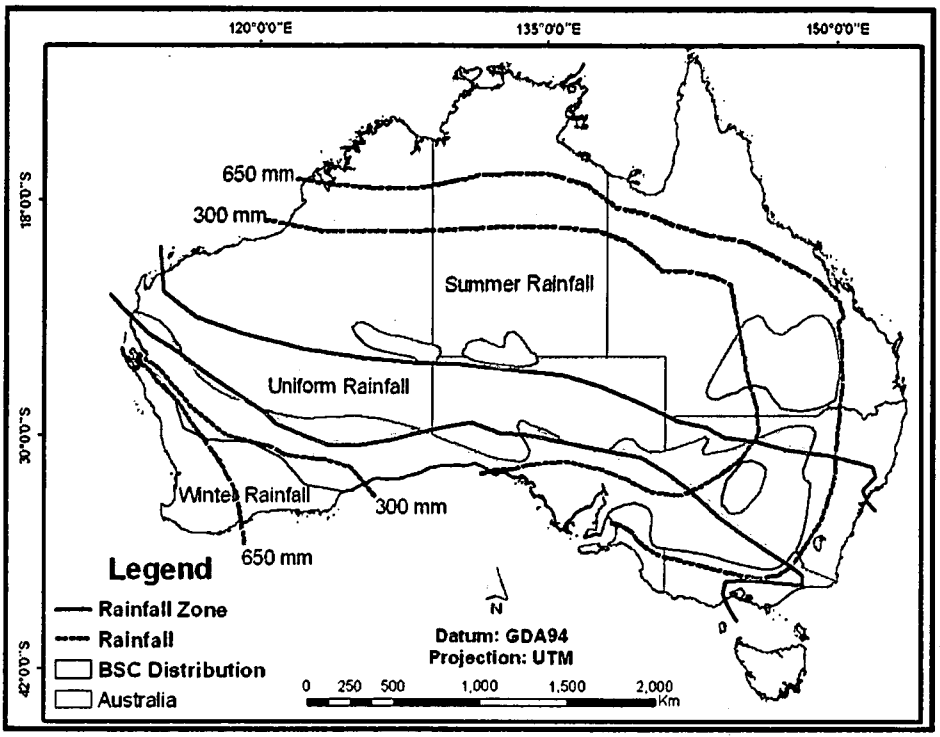

Figure 2-2. A schematic view of the distribution of lichen-dominated soil crusts in Australia in relation to average annual rainfall (Rogers & Lange, 1972; Eldridge, 2001).

Lichens, particularly squamulose, crustuse types, and cyanobacteria, mosses or liverworts have been considered mostly to be distributed on winter rainfall-dominated and calcareous soil areas (Rogers & Lange, 1971; Rogers, 1989, 1990; Eldridge, 1996b; Eldridge, 2001). Consequently these types of lichen crusts are most common over large areas of eastern and southern Australia, south-western Queensland, and areas of central Australia (Eldridge, 2001). According to Budel (2001) 83 genera of different BSC species have been reported from Australia including: 21 phycolichens, 4 cyanolichens, 10 cyanobacteria, 6 algae, and 42 mosses and liverworts. There is some controversy related to taxonomy of these organisms, and Eldridge (2001) estimated 70 genera subdivided as in Table 2-1. There has been very little examination of the effect of grazing (trampling) on the spatial patterns of BSC cover in the chenopod bioregion (Rogers & Lange, 1971; Graetz & Ludwig, 1978). To achieve such an examination, a sensitive monitoring method based on soil surface components would be valuable to measure the amount of change during past and current utilizations.

Table 2-1. Estimation of BSC diversity in Australia, adapted from Eldridge (2001)

BSC Groups	Families	Genera	Species
Lichens	18	25	80
Mosses	13	38	120
Liverworts	6	7	40
Total	37	70	240

2-5-5. BSC in South Australia

South Australia has a rich BSC flora (Rogers & Lange, 1971; Filson & Rogers, 1979; Catcheside, 1980; Howarth, 1983). Lichen species such as, *Psora decipiens*, *Endocarpon* spp., *Dermatocarpon* spp., *Heppia* spp., *Peltula* spp., *Collema* spp., *Chondropsis semiviridis* and mosses such as *Aloina bifrons, Fissidens* spp. *Barbula* spp., *Bryum campylothecium, Didymodon torquatus* have repeatedly been reported from rangelands of SA. In *Eucalyptus* spp., *Maireana* spp. and *Atriplex* spp. communities trampled by stock and feral animals (goats and rabbits), the lichen cover may be totally destroyed or restricted in occurrence to pedestals of soil beneath the bushes (Rogers & Lange, 1971; Eldridge, 2001).

In South Australia (Figure 2-2), BSC and their constituent organisms (Rogers & Lange, 1972; Eldridge, 2001) were studied at Maralinga (Eldridge, 1998b; Eldridge & Ferris, 1999), the Mid North Region (Hyde, 1994), Koonamore Vegetation Reserve (Rogers, 1974) and MFC (Rogers, 1970; Rogers & Lange, 1971; Howarth, 1983; Andrew & Lange, 1986a; Heshmatti, 1997). According to Eldridge and Tozer (1997a) BSC in South Australia are dominated by lichen species.

2-6. Rangeland Monitoring

The need to maintain sustainable land use requires that rangeland be monitored to detect early signs of land degradation so that the problem may be addressed in the early stages. Monitoring will also be required to assess the effectiveness of measures to control land degradation. Land degradation assessment is particularly difficult in rangeland areas (Pickup, 1989; Okin *et al.*, 2001a) because of the need to separate human-induced components of change from natural variation (Pickup, 1989; Bastin *et al.*, 1993a). In many areas, 70–90% of variation in vegetation production is caused by short and medium term rainfall variability and is beyond human control (Foran, 1987; Pickup, 1989). It is therefore essential to incorporate rainfall, vegetation cover, soil, BSC and other components of the rangeland surface in degradation assessment (Pyke *et al.*, 2002).

Monitoring has been identified as one of the most important, difficult, time consuming and contentious issues in rangeland management (Bastin *et al.*, 1993a). It implies a regular

assessment of change through time, and is generally viewed as being a continuing process rather than a one-time event (Rosentreter & Eldridge, 2002). Controversy still exits over what attributes to measure (Lauenroth & Laycock, 1989; Friedel, 1991), where to measure and how to measure (Jongman *et al.*, 1987; Krebs, 1989; Friedel, 1991). Rangeland characteristics such as: plant canopy cover, composition and structure; BSC and soil organisms; soil erosion and changes in topsoil play an important role in the development of attributes for monitoring of rangeland condition (Wilson *et al.*, 1984; Pickup, 1985, 1989; Tongway, 1995b; Friedel *et al.*, 2000; Pyke *et al.*, 2002). Choice of indicators and/or methods is strongly affected by what the management objectives are and who requires the information (Friedel *et al.*, 2000).

There are various approaches to monitor rangeland condition (NRC, 1994; NRCS, 1997). For example, vegetation can be monitored at the time a plot is established and resurveyed every few years. A second approach is to measure vegetation inside and outside an exclosure at the time of construction and again at appropriate intervals. However, both procedures require a period of several years to detect rangeland dynamics, conditions and trends. In this thesis the regional rangeland ecological dynamics of chenopod shrublands, in response to grazing, was considered within a landscape perspective. The main components which were considered for this thesis to evaluate landscape condition were BSC. Thus site selection, accurate and precise data collection and a reliable data analysis were identified as an important feature of the monitoring process. It is assumed that sampling locations within the study area have approximately the same site potential, (Ch.3) i.e., if any one of the sites is given the proper use or degree of rest, it could attain a condition equal to or approaching the best condition. The "best" condition site can be defined as quantitative expression of "excellent" condition.

2-6-1. Comparison of Ground-based and Remotely-sensed Methods

Ground-based methods have nearly always considered variables such as soil (e.g. depth, texture, pH, N, P, K, organic matter, surface and wind erosion), vegetation (e.g. species composition, cover, invasive plants, plant stress, reproductive capability of perennial plants, plant mortality, functional and structural grouping, plant community composition and density), BSC (e.g. cover, biomass and disturbance), hydrological function (e.g. runoff and infiltration), erosion (e.g. sheet, rill and gully) and climatic components (e.g. rainfall, temperature and evapotranspiration) for rangeland monitoring (NRC, 1994; NRCS, 1997; Herrick *et al.*, 2002; Pyke *et al.*, 2002). These methods work with high reliability in small areas but collecting data on all these variables is time consuming and expensive and, therefore, cannot be used over large areas (Bastin *et al.*, 1993a; NRC, 1994; NRCS, 1997).

Visual interpretation of passive remotely-sensed data in the form of aerial photography has been used in rangeland management from the 1930s (Poulton, 1975; Paine, 1981). The launch of Landsat in 1972 led to a new era of remote sensing with the ability of digital analysis of multi-spectral and multi-temporal data to be applied to rangeland management (Tueller, 1989). Remote sensing is a valuable tool by providing data for inventory and monitoring over time (Poulton, 1975; Paine, 1981; Tueller, 1987; 1989; 1995). Remotely-sensed data have the potential to be analysed repeatedly in a semi-automated way (Foran, 1987; Bastin *et al.*, 1993a; Campbell, 1996). Moreover, they allow the ability to map and monitor changes over time, can be rapidly acquired, have short turnaround time, can be digitally analysed (Poulton, 1975; Tueller, 1989; Campbell, 1996), allow complete coverage of large areas (Foran, 1987; Brook *et al.*, 2001), and are available at low or reasonable cost (Bastin *et al.*, 1993a). In Australia remote sensing systems (visible and infrared) with complete spatial coverage, repeated digital data acquisition, and an accessible historic data archive include Landsat MultiSpectral Scanner (MSS) (since 1981), Thematic Mapper (TM) (since 1988) and Advanced Very High Resolution Radiometer (AVHRR) (since ~1980) (Wallace *et al.*, 2004). Remotely-sensed approaches, using a limited number of variables such as total vegetation cover, litter and bare soil, have been used in attempts to discriminate rangeland condition over large areas (Bastin *et al.*, 1993a; Pickup *et al.*, 1994; Bastin *et al.*, 1998). These approaches have been reported to produce reliable results in large-scale studies allowing greater repeatability, which could not be possible with ground-based methods due to limitations of time and expense (Bastin *et al.*, 1993a).

2-6-2. Land Cover Indicators in Ground-based and Remotely-Sensed Methods

A stable and sustainable soil base is required for rangelands to yield a variety of multiple-use products, services, and amenities (Ellison *et al.*, 1951; Tongway & Smith, 1989; Tongway, 1994). The soil base, no matter what the soil type, needs an adequate ground cover of vascular and non-vascular plants, litter and stone for protection from rain, erosion and use (Tongway & Smith, 1989; Tongway, 1994, 1995b). O'Brien *et al.* (2003) defined ground cover as "... basal vegetation, litter, moss and lichen, or stone greater than 3 / 4-inch diameter." Qualitative rangeland condition and functionality checklists in the literature use a variety of indicators and descriptors focusing on various aspects of ground cover (Tongway & Smith, 1989; Tongway, 1994, 1995b; Pyke *et al.*, 2002). For example, in Pyke *et al.* (2002), 11 of the 17 indicators deal with some aspect of ground cover protection, such as rills, water flow patterns, bare ground, soil surface resistance to erosion and amount of litter. Land cover components from ground-based and remote sensing perspectives for different management objectives have been considered (Pickup, 1989; Bastin *et al.*, 1993a; Pickup *et al.*, 1994; Pyke *et al.*, 2002; O'Brien *et al.*, 2003).

Using the Society for Range Management Cover Types as the broad-scale vegetation classification base, ground cover threshold levels were developed to represent the threshold point at which a site in a particular cover type would begin to lose basic functionality, defined by increased soil erosion and loss of site sustainability (Tongway & Smith, 1989; Tongway, 1995b).

2-6-2-1. Canopy Cover as an Indicator in Ground-based and Remotely-sensed Methods

Because of canopy (aerial) cover effects on hydrological balance, erosion, climate, and global biogeochemical cycles, canopy cover change may be the most significant indicator of global environmental change. Canopy cover can be considered as an ecological and a management indicator. Canopy cover is considered the best indicator of protection of the landscape from degradation (Bastin *et al.*, 1993a; Pickup & Chewings, 1994). It is one of the commonly measured attributes in vascular and non-vascular plant sampling for rangeland assessment (Bastin *et al.*, 1993a; Pickup *et al.*, 1994) as well as being used in estimation in traditional ground-based methods (Bonham, 1989; Pyke *et al.*, 2002). Canopy cover of vascular and non-vascular plants is a characteristic expression of ecological dominance. In this study, vascular and non-vascular canopy cover is defined as the percent of surface that would be covered from the vertical direction (Mueller-Dombois & Ellenberg, 1974).

2-6-2-2. Advantages of Canopy Cover as an Indicator

Ecological dominance is a function of species biomass, while aerial cover values, which provide a close reflection of biomass rankings that depend on architecture of plants, are easier to determine. When comparing the concepts of frequency and density, Penfound (1945) believed that frequency is of the least importance, whereas cover delineates relative dominance more accurately (particularly reflecting competition for light). The abundance of canopy cover depends on available nutrients and the capacity of a soil to accumulate and store moisture. These factors decrease as a soil becomes degraded so the amount of cover is reduced (Pickup, 1989).

From a management viewpoint, canopy cover provides a variety of interpretations of direct concern to rangeland management, including erosion potential, the value of wildlife habitat, availability of forage and trends in rangeland condition. A suitable framework, such as a piosphere or the use of comparative method(s) of grazed and ungrazed (exclosure) rangeland, is required to discriminate the difference between the natural and human-induced change in canopy cover patterns of a given rangeland. The amount and distribution of canopy cover over time in arid and semi-arid rangelands has been used as an indicator of rangeland condition and to identify the processes of land degradation (Bastin *et al.*, 1993a; Pickup *et al.*, 1993; Pickup & Chewings, 1994). The application of this indicator has been well established in ground-based and remotely-sensed methods (Richardson & Wiegand, 1977; Tucker, 1979; Graetz & Gentle, 1982;

Warren & Hutchinson, 1984; Huete *et al.*, 1985; Graetz *et al.*, 1986; Arzani & King, 1994). Canopy cover also has the advantage of being easily measurable from a remote sensing perspective (Foran, 1987; Pickup, 1989; Bastin *et al.*, 1993a; Pickup *et al.*, 1993; Pickup & Chewings, 1994).

2-6-2-3. Limitations of Canopy Cover as an Indicator

Pickup (1989) reported that a single measure of canopy cover, which characterizes conditions at only one time, has strict restrictions as a degradation indicator. He stated that these limitations occur because of short-term changes in canopy cover from many other factors, including grazing and fire that occurs as plants dry off after rainfall. Furthermore, some kinds of degradation may not provide a reduction in canopy cover all over the area (Pickup *et al.*, 1994). For example, Warren and Hutchinson (1984) show that degradation in some semi-arid areas of the USA involves a reduction in perennial grass cover, an increase in shrub cover and eventual erosion of the soil surface. In addition, Pickup (1989) noted that cover could therefore be ambiguous unless the amount of shrub is known. He also pointed out that the difficulties of using canopy cover as a degradation measure are decreased if the spatial and temporal variability of the cover signal are considered in remotely-sensed methods. Moreover, cover is mostly representative of ecosystem change (without clear direction), rather than current rangeland condition and there is a difference between ecosystem change and rangeland condition change (Pickup, 1989).

2-6-2-4. Vascular Plant Cover

Vascular plant cover is frequently measured and claimed as a useful parameter for rangeland analysis in ground-based and remotely-sensed methods (Bastin *et al.*, 1993a; Bastin *et al.*, 1993b; Pickup *et al.*, 1993; Pickup *et al.*, 1994; Pyke *et al.*, 2002). It serves as a criterion of relative dominance and indicates the influence of plants on precipitation interception, soil temperature and soil conservation (Bastin *et al.*, 1993a; Pickup *et al.*, 1994). Compared with other parameters, such as species composition, biomass or productivity and soil components analysis, cover is relatively easily measured. Moreover, evaluation precise enough for research purposes generally does not require extensive fieldwork (Hanley, 1978; Bastin *et al.*, 1993a).

2-6-2-5. BSC Cover

BSC cover provides an indication of the extent to which the soil cycles nutrients, accepts rainfall, and resists erosion (Tongway & Smith, 1989). Trampling by animals and humans is known to reduce the BSC cover (Rogers & Lange, 1971; Anderson *et al.*, 1982; Klopatek, 1992). According to Anderson *et al.* (1982), who compared ungrazed areas in exclosures with adjacent grazed areas, there was 10 times greater moss cover, three times greater lichen cover and twice

as much algal cover inside the exclosures than outside. Kleiner and Harper (1977) found that the total cyanobacteria cover was nearly seven times as abundant on ungrazed areas. Klopatek (1992) reported that there is a relationship between BSC cover and undisturbed or less disturbed sites and believed that there is the possibility of gauging the level of ecosystem condition with BSC cover disturbance. More importantly, he noted that BSC disturbances are a useful early warning indicator if it is possible to detect them.

The cover of BSC has been used as an indicator of rangeland condition, particularly in shrublands, grasslands and woodlands of eastern Australia (Green, 1992; Eldridge & Koen, 1998). A soil surface condition system, which was developed in Australia (Tongway & Smith, 1989; Tongway, 1994) and uses the cover of BSC as one of its component attributes, provided a reliable estimate of the potential productivity of the surface, independent of assessments of vascular plants. According to this system, in the semi-arid woodlands of eastern Australia, cover and species composition of BSC are high on productive stable surfaces. On other surfaces, which were classified as unstable or unproductive, BSC are usually absent (Mucher *et al.*, 1988). In spite of these views, some recent literature (Eldridge & Koen, 1998; Rosentreter & Eldridge, 2002) has reported BSC cover as a weak indicator of rangeland condition.

2-6-2-6. Environmental Factors and Cover Change

Many environmental variables such as soil characteristics (e.g. pH, soil texture and soil depth); climatic components (e.g. rainfall and temperature); topography and physiography (e.g. slope, aspect and altitude); and, biotic factors, particularly human related ones, affect photosynthetic communities on a given rangeland. Identifying ecological processes without taking these variables into account may produce false results (McGarigal *et al.*, 2000).

2-7. Piosphere Concept in Ground-based and Remotely-sensed Methods

Many studies have emphasized the advantages of monitoring ecological indicators along environmental and management gradients such as slope, elevation and distance from watering points (Lange, 1969; Andrew, 1988; Ludwig & Tongway, 1992; Pickup *et al.*, 1994; Landsberg *et al.*, 1997; Austin, 2002). A large number of studies have convincingly demonstrated the existence of water-centred grazing gradients (piospheres) under broad-scale commercial grazing in Australian arid and semi-arid rangelands (Lange, 1969; Andrew, 1988; Bastin *et al.*, 1993a; Pickup *et al.*, 1994; Landsberg *et al.*, 1997). The detection of land degradation in ground-based and remotely-sensed methods for the purpose of pastoral land management often concentrates on the piosphere or grazing gradient that is evident in most well used paddocks. Water points are foci for grazing animals (Andrew, 1988) and their range away from the water point is defined by

how far they can travel before having to return for water. The higher activity around the water point results in an area where few or no vascular plants occur. As mentioned earlier, BSC is a response indicator (Klopatek, 1992; Eldridge & Koen, 1998) and thus, it is possible to measure the effects of livestock trampling on BSC cover in the framework of a piosphere.

In spite of extensive literature which shows that the piosphere is a robust framework to define livestock-related effects on rangeland ecosystems, successful research must avoid introducing systematic error (bias) and minimize random error (Hurlbert, 1984). Even on a well developed piosphere, there is a mixture effect caused by grazing, trampling and other environmental influences (Landsberg & Gillieson, 1996). Therefore, a method of separating grazing (trampling)-induced effects from environmental variations is required prior to piosphere establishment.

There is no strong agreement about the length of grazing gradient in sheep country. However, there is agreement that the main grazing impact of sheep probably occurs within 5 km of water (Landsberg *et al.*, 1992; Landsberg *et al.*, 1997). Graetz and Ludwig (1978) modelled the relationship between cover of chenopod shrubs and distance from water up to 3 km in pastures of southern New South Wales and South Australia. They found that sigmoid equations best described changes in ground cover. Shrub cover was low in the sacrifice zone within 400 m of the water point, increased rapidly in the first 1 km, and reached a stable maximum percentage cover 2-3 km from water. Overall, transect length depends on stocking rate, size of paddocks and vegetation type.

In remotely-sensed methods that were based on the grazing gradient there is strong agreement about the suitability of this framework for separation of grazing-induced effects in the landscape from those due to other factors (Bastin *et al.*, 1993a; Pickup *et al.*, 1994; Bastin *et al.*, 1998; Washington-Allen *et al.*, 2004). Bastin *et al.* (1998) and Brook *et al.* (2001) have reported that suitable stratification of an area into landscapes or land units prior to employing a remotely-sensed method is necessary.

Overall, according to extensive studies in central Australia, the grazing effect detected in aerial cover by remote sensing was described as: "normal gradient", "composite gradient", "inverse gradient" and "no gradient" (Figure 2-3a-d) (Pickup *et al.*, 1993; Pickup & Chewings, 1994). In normal gradients that "...occur involving erosion, soil structure breakdown or other damage to plant community productivity, there will be, on average, a gradual increase in vegetation cover with distance from water" (Pickup & Chewings, 1994). Normal gradients are often characterised by lack of recovery after a rainfall pulse, which means that grazing gradient is permanent and if there is recovery, it is temporary (Pickup & Chewings, 1994). "Inverse gradients" describe a decrease in cover with distance from water and may intensify as the

landscape is progressively grazed out in a dry period (Bastin *et al.*, 1993a). "Composite grazing gradient", when normal and inverse grazing gradients are combined in the same landscape type, exhibit cover that decreases with distance from water up to particular distance and then begins to increase (Pickup & Chewings, 1994). Finally, the "no gradient" pattern means there is light grazing on the paddock and there are no discernable grazing gradient patterns (Pickup & Chewings, 1994). This study aims to compare derived gradient patterns from ground-based cover analysis (Ch. 4), ground-level spectral modelling (Ch.6) and graphical analysis of image derived gradients (Ch.7) with these frameworks.

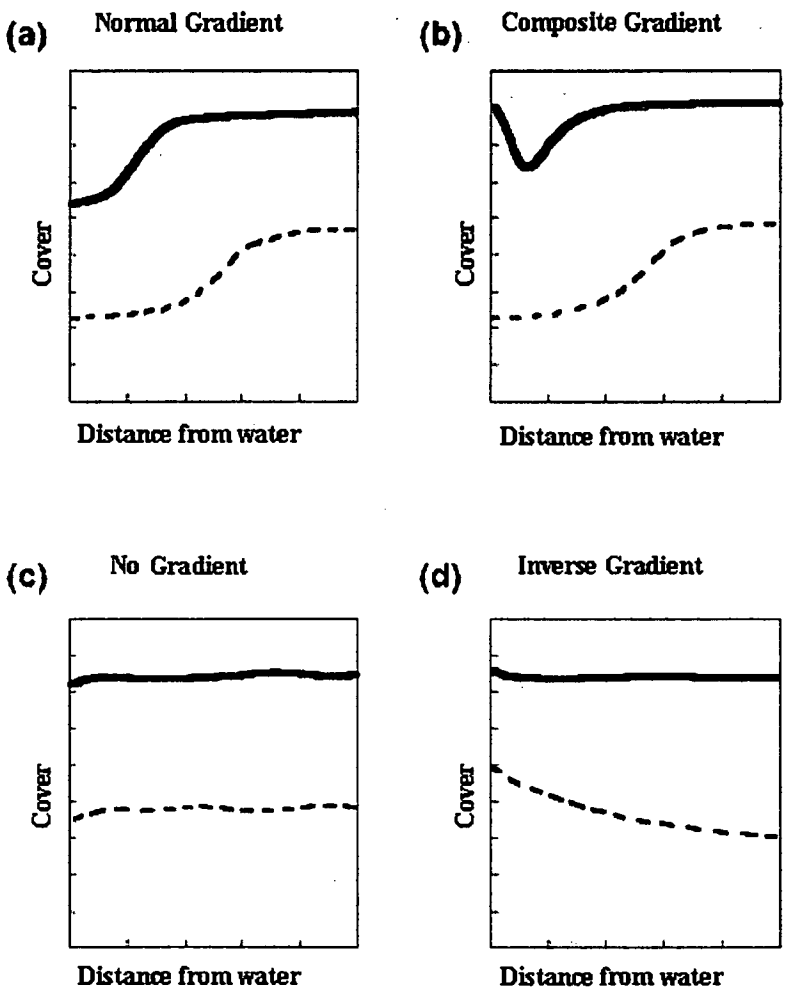

Figure 2-3. Stylized examples of grazing gradient types: a) is permanent normal gradient; b) is temporary composite gradient; c) no gradient; and, d) is a temporary inverse gradient. The solid line shows wet period average cover and dry period cover is indicated by the dashed line (Bastin *et al.*, 1993a).

2-8. Characteristics of Remotely-sensed Methods

2-8-1. Electromagnetic Radiation and Remote Sensing

Remote sensing technologies are based on ElectroMagnetic Radiation (EMR). EMR is a continuous form of energy, which is transmitted through space at an approximate velocity of 3 $\times 10^{8}$ ms $^{-1}$ in the form of magnetic and electrostatic fields. EMR is ordered by wavelength (Table 2-2), frequency or photon energy (Lillesand & Kiefer, 2000; Campbell, 2002). The visible part of the EMR spectrum runs from 400 to 700 nm. Photons in the 400-500 nm bands cause the sensation in the eye that humans call blue. The 500-600 nm response we call green, and the 600-700 nm band we call red. Beyond 700 nm or so, i.e., the infrared region, the eye becomes insensitive to the photons. The infrared region can be divided into three sub regions as Near Infrared (NIR) (700-1100 nm), Mid Infrared (MIR / 1150-1750 nm) and Short Wave InfraredRed (SWIR / 2080-2350 nm). See "*The Photonics Design and Applications Handbook*" (Pittsfield, 1996) for more details of EMR energy. Spectral bandwidth is the width of an individual spectral channel in the sensor. The narrower the spectral bandwidth, the narrower the absorption feature the spectrometer will accurately measure (Clark, 1999). Some systems have a few broad channels, not contiguously spaced and, thus, are not considered spectrometers (Clark, 1999). Examples of these types of sensors include the Landsat MSS, TM systems or the MODerate Resolution Imaging Spectroradiometer (MODIS), which can not resolve narrow absorption features. On the other hand, hyperspectral sensors like the NASA JPL Airborne Visual and Infra-Red Imaging Spectrometer (AVIRIS) system have many contiguous bandwidths. Overall, there are four general parameters, which describe the capability of a sensor in regards to spectroscopy and remote sensing: 1) spectral range; 2) spectral bandwidth; 3) spectral sampling; and, 4) signal-to-noise ratio (S/N) (Clark, 1999). Spectral range is important to cover enough diagnostic spectral absorption to solve a desired problem.

Table 2-2. Spectral bands and wavelength range of each band adapted from Dudycha (2003)

Spectral Band	Wavelength
Gamma Rays	< 0.03 nm
X Rays	0.03 - 3 nm
Ultraviolet	3 nm - 400 nm
Visible	400 nm - 700 nm
Infrared	700 nm - 2400 nm
Microwave	1 mm - 1 m
Radio	> 1 m

2-8-2. Sensor Selection in Rangeland Monitoring

One of the important stages in remotely-sensed methods is the selection of a suitable sensor and image, particularly in temporal-based or change detection studies (Reed *et al.*, 2003; White *et al.*, 2003; Lu *et al.*, 2004). Table 2-3 and Figure 2-4 present some of the commonly used sensors in rangeland monitoring, particularly in Australia. Previous studies have mostly been conducted using multispectral datasets such as Landsat imagery in rangeland monitoring (Graetz & Gentle, 1982; Graetz *et al.*, 1983; Pickup & Nelson, 1984; Graetz *et al.*, 1986; Green, 1986; Graetz *et al.*, 1988; Pickup & Chewings, 1988b, a; Bastin *et al.*, 1993a; Bastin *et al.*, 1993b; Pickup *et al.*, 1993; Pickup *et al.*, 1994; Pickup & Chewings, 1994; Cameron & Lewis, 1996; Bastin *et al.*, 1998; Washington-Allen *et al.*, 2003; Ramsey *et al.*, 2004; Washington-Allen *et al.*, 2004). These Australian studies have used Landsat datasets, particularly MSS for developing indices such as the perpendicular vegetation index (commonly called PD54) (2-10-3) (Pickup *et al.*, 1993; Pickup & Chewings, 1994) and the Soil Stability Index (SSI) (2-10-2) (Pickup & Nelson, 1984). More recently Landsat data were also used in the USA for soil stability (Washington-Allen *et al.*, 2003) and piosphere analyses (Washington-Allen *et al.*, 2004).

2-8-3. Multispectral Dataset Capabilities (Landsat TM as an Example)

Landsat TM is an advanced and multispectral-scanning earth resources sensor planned to achieve higher image resolution, sharper spectral separation, improved geometric reliability, greater radiometric accuracy and higher resolution than the MSS (Campbell, 1996). TM data are simultaneously scanned in seven spectral bands. Since 1983, this satellite has provided repetitive and synoptic coverage using moderate-resolution multispectral imagery in Australia. The characteristics of TM data are selected to maximize their capabilities for the detecting and monitoring of natural resources (Table 2-4).

Figure 2-4 shows a typical spectral reflectance response of healthy vegetation, and presents some general characteristics of reflectance spectra and their interpretation in relation to a multiband system, such as the Landsat MSS and TM. In the visible part of the spectrum, the vegetation absorbs most of the blue light, reflects some of the photons in the green band (usually between 10 and 20%), and absorbs most of the photons in the red band. The result is that the vegetation is seen as green. In the infrared region, however, healthy vegetation has a much higher reflectance. Although our eyes are not sensitive to these wavelengths, artificial sensors can record such photons and display the results in some form of imagery, giving apparently different colours by using different band combinations.

Table 2-3. Some of the available remote sensing data for rangeland monitoring

Sensor / Year of launch	Spatial Resolution (m)	Spectral Resolution	Temporal Resolution (day)	Cost ($Aus /km^2)
Landsat MSS (1972-1997)	80	0.5 - 1.1 μm, in 4 broad bands (green, red and infra-red)	16-18	$0.02
Landsat (TM) (1983)	30	0.45-12.5 μm, 7 broad bands (blue, green, red and near infra-red and thermal)	16	$0.03
Landsat Enhanced Thematic Mapper Plus (ETM+) (1999)	15/30/60	0.45-12.5 μm, in 8 broad bands (panchromatic, blue, green, red, near infrared, short wave infrared, thermal infrared)	16	$0.03
Satellite Probatoire d'Observation de la Terre (SPOT) (1986)	5/10/20	0.51-0.73 μm, in 3 bands (green, red & infra-red) + visible infra red panchromatic	2.5-26	$1.58
Advanced Space Borne Thermal Emission and Reflection Radiometer (ASTER) (1999)	(3×15), (5×30), (5×90)	0.52-11.65 μm, visible and infrared	4-16	$0.04
MODerate Resolution Imaging Spectroradiometer (MODIS) (1999)	(2 × 250), (5 × 500), (29 × 1000)	36 bands visible and infrared	1-2	Free
Space Imaging (IKONOS) (1999)	0.82/3.2	Panchromatic, visible and infrared	3-5 (off Nadir)	$38.00
Earth Watch (QuickBird) (2001)	0.61/2.44	Panchromatic, visible and infrared	1-3.5 (off Nadir)	$31.25
Hyperion (2000)	30	220 unique channels. VNIR (70 channels, 356 nm - 1058 nm), SWIR (172 channels, 852 nm - 2577 nm)	16	$1.12 to 2.50
Compact Airborne Spectrographic Imager (CASI)	variable	19 bands , 440-930 nm	variable	$200.00 to 300.00
HyMap	variable	128 bands / 400 -2500 nm	variable	$200.00 to 300.00

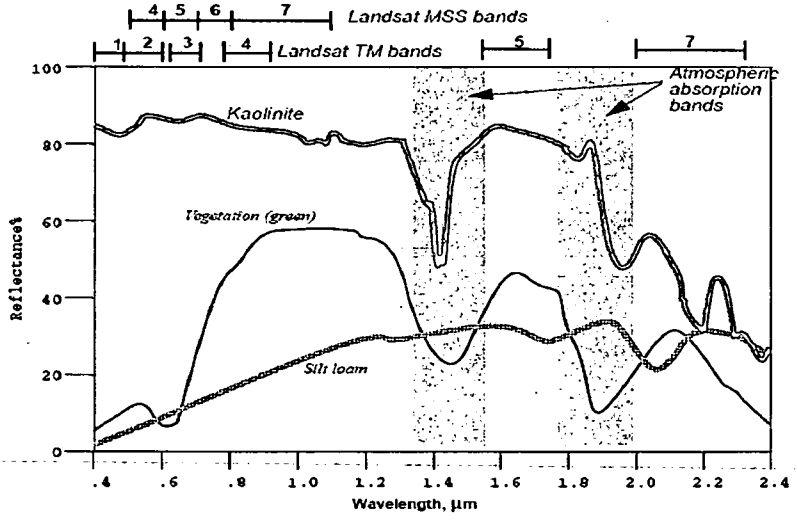

Figure 2-4. Typical spectra of green vegetation, silt loam and kaolinite as examples *vs.* TM and MSS visible-NIR bands positions in the EMR spectrum (0.4 to 2.4 μm), with atmospheric absorption bands (Leica Geosystems GIS & Mapping LLC, 2003)

Table 2-4. Key characteristics and the application of Landsat TM visible-NIR bands (Lillesand & Kiefer, 1994; Campbell, 1996; NASA, 2004)

Band number	Spectral Range (μm)	Resolution (m)	EMR region	Application
1	0.45-0.52	30	Blue	Coastal water mapping, differentiation of soil from vegetation; has poor penetration through haze
2	0.52-0.60	30	Green	Vegetation vigour assessment
3	0.63-0.69	30	Red	Chlorophyll absorption for vegetation discrimination; also has high iron oxide reflectivity
4	0.76-0.90	30	NIR	Determining healthy green vegetation, vegetation types, vigour, biomass content and soil moisture discrimination; delineation of water bodies
5	1.55-1.75	30	MIR	Vegetation and soil moisture content; differentiation of cloud from snow
7	2.08-2.35	30	SWIR	Discrimination of rock types and hydrothermal clay mapping

TM bands 1, 2, and 3 are in their appropriate locations (blue, green and red); but, in order to avoid added clutter in the diagram, the cut offs are not shown. A normal colour image made from bands 1, 2, and 3, coupled to blue, green, and red computer display channels respectively, would show healthy vegetation as green with low brightness. Typically, bands 4, 3 and 2 can be combined to make false-colour composite images where band 4 is represented by red, band 3, green, and band 2, blue. This band combination makes vegetation appear as shades of red, brighter red indicating more vigorously growing vegetation. Soils with no or sparse vegetation will range from white (dry sands) to greens or browns depending on moisture and organic matter content. In addition to the ability to combine bands, band ratios and spectral mixing present data reductions which provide advantages of these technologies in rangeland assessment (Smith, 1990; Lillesand & Kiefer, 1994; Pickup *et al.*, 1994; Campbell, 1996). The broad dips at 1.4 and 1.9 μm of the vegetation signature (Figure 2-4) are due to water absorption. As a plant loses water, these bands become shallower, and provide an indicator of stress. It should be noticed as indicated in Figure 2-4, these also broadly correspond to the atmospheric water absorption bands.

2-8-4. Limitations of Remotely-sensed Methods for Arid and Semi-arid Rangelands

Monitoring vegetation components of arid environments using remotely sensed imagery is complicated by the fact that vegetation cover is low and varies greatly over space and time (Huete *et al.*, 1985; Huete & Jackson, 1988; Pickup, 1989; Smith *et al.*, 1990; Okin *et al.*, 1999; Asner & Heidebrecht, 2002). This variability has several causes, in particular: low, variable and unpredictable rainfall; patchy infertile soils; bright and high reflectance and grazing by introduced animals such as livestock and rabbits (Pickup, 1989; Bastin *et al.*, 1993a; Pickup *et*

al., 1993; Pickup *et al.*, 1994). Some other key factors such as: extensive soil background; low vegetation cover with resulting high soil exposure; different spectral signatures for the same plant when compared to their spectra in humid areas; and shadow, create difficulties in interpreting remotely-sensed information in arid rangelands (Pickup, 1989; Tueller, 1989; Okin *et al.*, 2001b; Asner & Heidebrecht, 2002). Depending on the resolution (e.g. spatial, temporal and spectral) of remotely-sensed data, these issues create different levels of imprecision in image processing. Total photosynthetic plant cover is usually quite low and less than 20-30%, so images are often distinguished by extensive soil background, and individual vascular plant and BSC canopies are naturally small not reaching the spatial size of usual Landsat like satellite image pixels (Huete *et al.*, 1985; Foran, 1987; Huete & Jackson, 1988; Smith *et al.*, 1990; Okin *et al.*, 1999; Okin *et al.*, 2001b; Asner & Heidebrecht, 2002). Moreover, identifying soil components using remotely-sensed data in arid and semi-arid situations is more difficult than identifying photosynthetic plants, because of low and unpredictable rainfall (moisture), and low amounts of soil fertility (Huete *et al.*, 1985; Pickup & Chewings, 1988b; Okin *et al.*, 2001b; Asner & Heidebrecht, 2002) with soil patches rarely reaching the spatial scale of satellite image pixels (Huete & Jackson, 1988; Smith *et al.*, 1990; Okin *et al.*, 1999; Okin *et al.*, 2001b; Asner & Heidebrecht, 2002). Therefore, accurate estimates of soil and vegetation cover are difficult to achieve, and so too is distinguishing naturally caused variability from human-induced variability (Bastin *et al.*, 1993a; Okin *et al.*, 1999; Asner & Heidebrecht, 2002).

2-9. Change Detection, Remote Sensing and BSC

2-9-1. Change Detection

This study aims to characterize, model and develop remotely-sensed methods for BSC detection based on temporal image selection, so a review of change detection theory and research is necessary. Because of the difficulties of spatial detection of biophysical components, the values (conditions) of rangeland surface features are usually considered by temporally-based methods of change detection. For example, in rangeland condition assessment, ecologists need to measure quality and quantity of rangeland surface components. Ground-based methods have obvious advantages in directly measuring these variables; however they are labour and therefore cost-intensive (see 2-6-1). Thus, remote sensing technologies have the potential to become a surrogate tool by measuring the value of change between two temporally separated images to define status of rangeland condition (Bastin *et al.*, 1993a; Pickup *et al.*, 1994; Pickup & Chewings, 1994).

2-9-2. Main Biophysical Components of Arid and Semi-arid Rangelands

Identification of BSC using current remote sensing technologies is extremely difficult. However, there is a possibility of land cover classification, and thus the first step for change detection is to define which components are useful indicators of condition. Natural spatial and temporal heterogeneity of perennial, annual and BSC components, as well as inclusion of soil, litter, rock or stone and shadow contribute to mixed interactions with EMR energy. Non-biological components particularly in a short temporal period (study years with low amount of rainfall in comparison with mean), are almost constant. However, climatic and biological components are not constant variables. Therefore, for remote-sensing of BSC, it is important to consider weather and phenological patterns for a temporal-based remote sensing.

2-9-3. Remotely-sensed Methods of Rangeland Monitoring

Four basic approaches have been used to estimate the amount of vegetation cover change from remotely-sensed data: mixture models (Smith *et al.*, 1990), calibrated cover radiance relationships (Graetz *et al.*, 1988), neural networks (Baret *et al.*, 1995) and generalized vegetation indices (Rouse *et al.*, 1974; Tucker, 1979). This study is based on the fourth approach: using indices and raw image differencing to conceptualize BSC effects on remotely-sensed data and possible methods of detecting these effects.

2-10. Remote Sensing Indices

Spectral indices are simple mathematical combinations of two or more spectral values to produce a single value that describes a photosynthetic organism's quality or condition (Hall *et al.*, 1992; Wood & Lakshmi, 1993). The basic idea of a spectral index is to collapse the multispectral or hyperspectral remote sensing values to a particular measure, which is related to some characteristics (i.e. vegetation cover and greenness) of an object (Rundquist, 2000; Rundquist, 2002). The SR, NDVI, PD54 and Soil Adjusted Vegetation Index (SAVI) are examples of the most commonly used vegetation indices to analyse the green cover of photosynthetic vegetation and / or soil noise effects in image processing. Studies have been conducted using these kinds of indices for rangeland condition monitoring (Graetz *et al.*, 1983; Foran & Pickup, 1984; Bastin *et al.*, 1993a), and some of the commonly used indices are presented in Table 2-5.

Table 2-5. Some of the vegetation, soil noise and BSC indices (all of these indices were tested using image data, however, indices including NDVI, PD54, RAT57, SSI, CI and BSCI were used in different chapters of this thesis).

Index	Acronym	Formulation	Reference
Simple Ratio	SR	Nir / Red	(Tucker, 1979)
Difference Vegetation Index	DVI	Nir-Red	(Richardson & Everitt, 1992)
Normalized Difference Vegetation Index	NDVI	$[(R_{nir} - R_r) / (R_{nir} + R_r)]$	(Rouse *et al.*, 1974; Tucker, 1979)
Normalized Difference Vegetation Index	NDVI	$[(R_{895} - R_{675}) / (R_{895} + R_{675})]$	(Fuentes *et al.*, 2001)
Transformed Normalized Difference Vegetation Index	TNDVI	[(Band 4 - Band 3)/(Band 4 + Band 3) +0.5]^(1/2)	(Deering *et al.*, 1975)
Perpendicular Distance	PD54	G *vs.* R (MSS)	(Pickup *et al.*, 1993)
Infra-red Percentage Vegetation Index	IPVI	(NDVI+1)/2 or Nir /Nir +Red	(Crippen, 1990)
Ratio of Band Counts	RAT57	(B4-B5)/(B4-B7) (MSS)	(Foran & Pickup, 1984)
Perpendicular Vegetation Index	PVI	$[(RS_r - R_r)^2 + (RS_{nir} - R_{nir})^2]^{0.5}$ or sin(a) NIR-cos (a) red	(Richardson & Wiegand, 1977)
Soil Adjusted Vegetation Index	SAVI	$[(R_{nir}-R_r) / (R_{nir}+R_r+L)](1+L)$	(Huete, 1988)
Soil Stability Index	SSI	(B2 / B3) – (B1 / B 3) (MSS)	(Pickup & Nelson, 1984)
Spectral Crust Index	CI	1-(Red-Blue)/(Red+Blue)	(Karnieli, 1997)
Biological Soil Crust Index	BSCI	$1-L\times\lvert R_{red}-R_{green}\rvert/R^{mean}_{GRNIR}$	(Chen *et al.*, 2005)

2-10-1. Normalized Difference Vegetation Index

NDVI, which is a combination of red and NIR reflectance measurements, is the most commonly used index in the world (Ramsey *et al.*, 2004) and has been used extensively as an indicator of the state of vegetation over many spatial and temporal resolutions. It is based on the difference between the maximum absorption of radiation in the red spectral band and the maximum reflection of radiation in the near-infrared spectral bands. Values of the NDVI range between –1.0 and +1.0, but are usually positive for soil and vegetation. Denser and/or healthier vegetation will have higher values. NDVI values for vegetation usually offer a means of efficient and objective evaluation of phenological characteristics (Justice *et al.*, 1985; Reed *et al.*, 1994). Several studies have concluded that NDVI can be linearly transformed between spatial scales (Hall *et al.*, 1992; Wood & Lakshmi, 1993). Lacking the plants' absorption / reflectance mechanisms, soil spectra typically do not show such a dramatic spectral differences on this index (Karnieli, 2003).

2-10-1-1. Difficulties of Using the NDVI

Before using the NDVI, it is important to understand and outline the difficulties which can be expected using this index. There is increasing evidence that NDVI cannot be accurately transformed between field and satellite scales in a linear fashion (Quattrochi *et al.*, 1997; Goodin & Henebry, 1998; Goodin & Henebry, 2002). Indeed, there is little knowledge of interactions between spatial heterogeneity in a photosynthetic canopy and spatial scale of measurement, although researchers are beginning to address such issues (Goodin & Henebry, 1998; Rundquist, 2000; Goodin & Henebry, 2002; Rundquist, 2002).

Another problem with NDVI is that often it is not a product of the process with which it is correlated (Huete, 1988; Briggs *et al.*, 1997; Carlson & Ripley, 1997). That is, NDVI can be an indicator of different things such as at different locations and times (both seasonally and inter-annually). These include dissimilarities in canopy background (i.e. substrate) reflectance characteristics: the presence of leaf litter, senescent (i.e. standing dead) vegetation, and woody materials; differences in green vegetation coverage, density, geometry and phenology; short and long-term climate variation; canopy bi-directional reflectance properties; and contrasting management practices (Huete, 1988; Briggs *et al.*, 1997; Carlson & Ripley, 1997). Li *et al.* (1996) have shown that the scene brightness can account for up to 30% of the variation of NDVI for some land covers. Another problem is the expected difference between NDVI measured at the surface and from space, which is related to dissimilar atmospheric attenuation of red and near infrared radiation (Carlson & Ripley, 1997).

2-10-1-2. Application of the NDVI in Australia

The NDVI has been frequently used in Australia, particularly using coarse to moderate spatial resolution imagery such as AVHRR/ NOAA, Landsat MSS, TM and SPOT satellite data (Roderick, 1994; Cridland *et al.*, 1995; Cameron & Lewis, 1996; Cridland & Fitzgerald, 2001; Lovell & Graetz, 2001; Allan *et al.*, 2003). For example, the NDVI has been used for rangeland monitoring (Roderick, 1994; Cridland *et al.*, 1995; Cridland & Fitzgerald, 2001), grassland dryness and fire potential (Paltridge & Barber, 1988), for predicting fuel curing at landscape scales from NOAA /AVHRR and SPOT data (Allan *et al.*, 2003), and for evaluation of pre- and post-fire state with SPOT2 satellite imagery (Chris *et al.*, 2004). Cameron (1995) used this index for vegetation cover estimation at MFC with significant results. Likewise, it has been used for predictive modeling for a natural resource management at Australasian continental scale (McVicar *et al.*, 2003). Lu *et al.* (2003) showed linear and curvilinear relationships between field-measured Leaf Area Index and NDVI and used these relationships to separate land cover components and infer Leaf Area Index across Australia. There is little evidence of taking BSC

distribution into account when undertaking image processing. Consequently, there is little information about the influence of BSC on the results of these projects. See Chapters 5, 6 and 7 for more details of NDVI.

2-10-2. Soil Stability Index

SSI was originally developed on the red-yellow soils within Australia's central arid region by stratifying a landscape's land-form into four categories of erosional status: stable, transitional, depositional and erosional (Pickup & Nelson, 1984). Reflectance in the four MSS bands was measured using an airborne Exotech radiometer for groups of surfaces in each category and the responses plotted against each other to determine which band combinations (10 nonreciprocal combinations) best separated the erosion categories in Cartesian data space. Pickup and Nelson (1984) found that the ratio of the MSS band 4 (green / 0.5 - 0.6 μm) divided by the near NIR band 6 (0.7 – 0.8 μm) or the 4/6 ratio, plotted against the ratio of band 5 (red / 0.6 - 0.7 μm) divided by band 6 or the 5/6 ratio best discriminated the surfaces of this parameter space (Figure 2-5). Because the vector cloud was parallelogram shaped, they determined that either measurement of the perpendicular distance of each surface's coordinates from a bounding upper or lower parallel line provided a quantitative measure of soil stability or susceptibility to erosion which they called the Soil Stability Index (Pickup & Nelson, 1984). Pickup and Nelson (1984) found for their MSS imagery the range of values for the 1/3 band ratio to be 0.5 to 0.9 and for the 2/3 band ratio to be 0.75 to 1.5. Using these values from TM imagery could be about -0.25 to -0.6 (see Chapter 5 for more details of the SSI analysis). It has been shown to work well in central Australian landscapes where there is a strong relationship between vegetation cover and erosion status. The only application of this index for MFC with successful results was applied by Cameron (1995).

2-10-3. Perpendicular Vegetation Index (PD54)

The soil and vegetation lines (Figure 2-6) define a two-dimensional spectral construct for each of the green-red paired reflectances (Gitelson *et al.*, 2002). Soil has properties which cause the ratio of NIR and visible red reflectance to plot in a linear fashion. It also displays a linear relationship in the data space of visible red versus visible green reflectances. For very homogenous soils, these lines may be very short and for soils that vary in type and moisture content, this line may be stretched significantly (Banman, 2001). This means that as light energy comes into contact with the individual soil particles, each particle will reflect proportionately similar amount of green, red and NIR wavelengths (Banman, 2001).

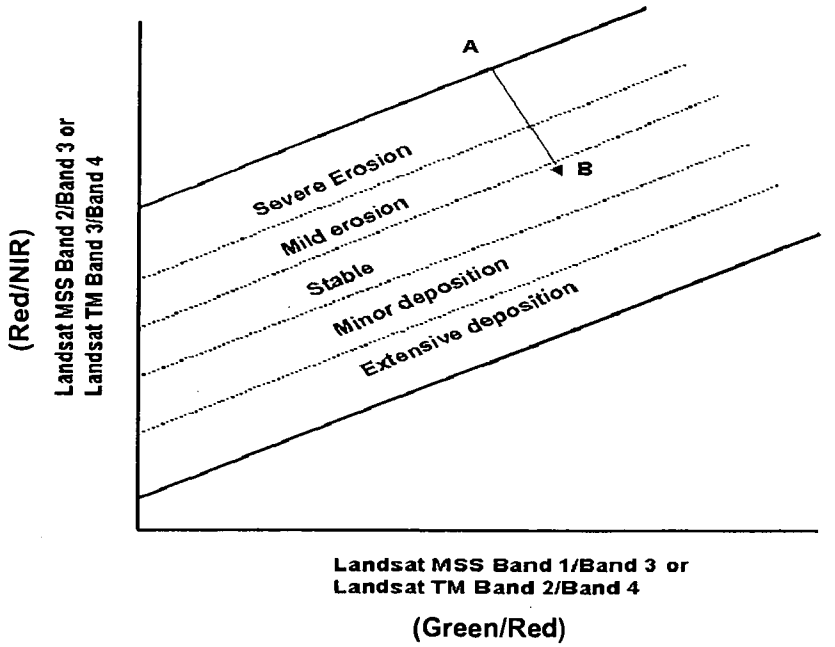

Figure 2-5. MSS bands 1/3 (4/6) *vs.* 2/3 (5/6) and TM bands 2/4 *vs.* 3/4 and the discrimination of landform erosion states by the SSI. SSI is calculated as the magnitude of the line AB (Pickup & Nelson, 1984; Pickup & Chewings, 1986; Washington-Allen, 2001).

Orthogonal or perpendicular difference indices such as PVI or PD54 overcome the soil background effect by estimating vegetation variables in relation to a soil line (Williamson, 1989). The soil line represents the background soil reflectance present in the remotely-sensed data (Cameron, 1995). In arid rangelands where soil reflectance is bright in all wavebands, vegetation points would conceivably occur below this soil line as vegetation reflectance is lower than bare ground reflectance (Cameron, 1995). In a cross plot of MSS bands 5 and 4, Pickup *et al.* (1993) showed that bare soil, rock or stone plots are well separated from vegetated targets. They found that data tended to fall between two parallel lines.

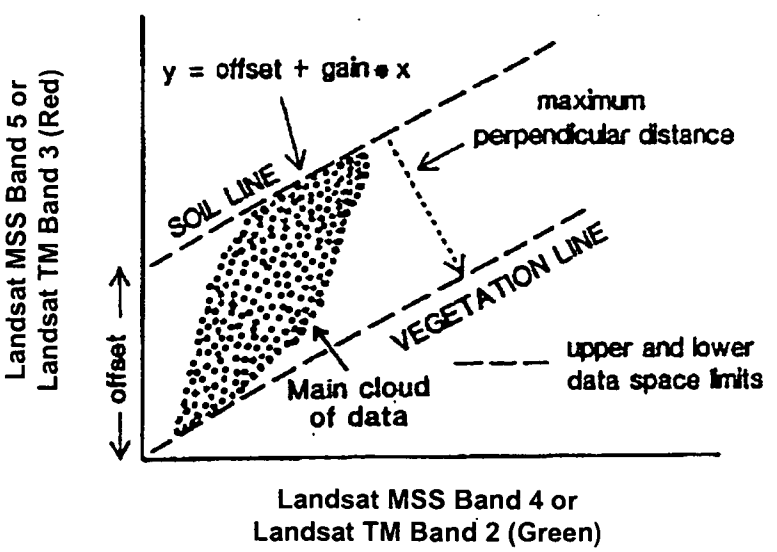

Figure 2-6. Basis of the PD54 in MSS data space adapted from Pickup *et al.* (1993)

In Figure 2-6 the upper spectral line represents the soil line and the lower spectral line corresponds to a vegetation line and represents the maximum amount of cover present in the image. The developed index was called PD54. Perpendicular Distance between band 5 and band 4 (PD54) is now commonly used for rangeland monitoring in Australia (Bastin *et al.*, 1993a; Bastin *et al.*, 1993b; Pickup *et al.*, 1993; Pickup *et al.*, 1994; Pickup & Chewings, 1994; Cameron, 1995; Bastin *et al.*, 1998; Brook *et al.*, 2001; Clarke, 2004). It is used within a grazing gradient framework to detect response of vegetation cover to rainfall in wet and dry periods, and is thought to closely relate to the percentage cover in a wide range of arid region vegetation types.

PD54 does have some limitations (Pickup *et al.*, 1993; Bastin *et al.*, 1998; Brook *et al.*, 2001). These researchers noted that it was not a good index for communities in topographically undulating areas as slope affects the amount of reflected radiation. Moreover as Brook *et al.* (2001) noted, it has problems when applied to some surfaces such as dark gibber or used in an area where rainfall is not the major factor driving vegetation cover change. Cameron (1995) applied this index at MFC with successful results.

2-10-4. Crust Index

A spectral Crust Index (CI) (Karnieli, 1997) has been developed, based on the normalized difference between the red and the blue spectral values (Table 2-5). Applying the index to a sand dune environment, it has been shown that the CI can be used to detect and to map, from remote sensing imagery, different lithological morphological units, such as, active sands, crusted interdune areas and playas, which are expressed in the topography. As a mapping tool, the CI is much more sensitive to ground features than the original images data. The application of the CI can be performed with imagery acquired by any sensor containing the blue and red bands (Karnieli, 1997). It should be noted that this index was developed on a cyanobateria-dominated area.

2-10-5. Biological Soil Crust Index

Biological Soil Crust Index (BSCI) was recently developed in China (Chen *et al.*, 2005) using both a radiative transfer simulation (6S) and an analysis of a Landsat ETM+ image. As presented in Table 2-5 the equation of this index is:

$$BSCI=1-L\times|R_{red}-R_{green}| / R^{mean}_{GRNIR} \qquad \text{equation 2-1}$$

where R_{green}, R_{red} are, respectively, the reflectance of the green and red band, which correspond to bands 2 and 3 for Landsat ETM+ sensor. "L" is an adjustment parameter to amplify the absolute difference between R_{green} and R_{red}. In case the numerator gets a negative value the

modulus of the difference is taken, "L" is restricted within the range from 2 to 4. "^{mean} GRNIR" is the mean reflectance of green, red and the near-infrared band, which subsequently refer to bands 2, 3, 4 for the ETM+ sensor. Chen *et al.* (2005) have shown using a simulated model that ETM+ data could be used, after atmospheric correction, to detect BSC if 33% or more of any pixel was covered by BSC. They have applied their indices with real imagery with a Kappa coefficient of 0.82 and overall accuracy of 94%. They claimed that BSCI has good potential for BSC detection and mapping in cool and cold lichen-dominated rangelands.

2-10-6. Ratio of Band Counts / RAT 57 Index

Literature gives little attention to the use of MIR and SWIR bands of multispectral imagery. The only index used in Australia is the RAT57 (Foran & Pickup, 1984), which is based on the subtraction ratio of (B4 – B5) / (B4-B7) in MSS data. It was developed for cover estimation and was used for cover and productivity estimation by Foran (1987) in central Australia.

2-11. Summary

Rangelands are important throughout the world including Australia and the chenopod shrublands is one of the most widespread bioregions in Australia. Rangelands have been degraded since European settlement and, as a consequence, various criteria and indicators have been used for rangeland monitoring to assess rangeland condition. BSC cover has been used as an indicator, but there is no strong agreement that BSC cover is a good indicator for rangeland condition assessment. This could be because previous studies have used data taken in dry conditions, when it is difficult to differentiate BSC from bare soil.

There are two groups of methods for rangeland monitoring: ground-based and remotely-sensed methods. Remotely-sensed methods have advantages over ground-based methods including higher cost-effectiveness and broader coverage. Land cover estimation to determine land degradation is a common procedure in remotely-sensed methods, and such procedures are usually placed in a piosphere framework because distance from water is a good indicator of grazing pressure and degradation. Remotely-sensed methods for land cover estimation have used the spectral characteristics of plants and soils and image intepretation of multi- or hyper-spectral imagery for change detection. Indices such as NDVI, SSI and PD54 are the most commonly used indices and methods for rangeland monitoring. These remotely-sensed indices have been applied to areas in which BSC are common, but with little consideration of the effect of BSC on the indices. There is little information about the effect of BSC on the remotely-sensed indices. This study aims to investigate the variance of BSC cover in the framework of the piosphere, and, as a second stage, the effect of BSC on various remote-sensing indices.

CHAPTER 3

3. GENERAL METHODS

This Chapter
General aspects of BSC monitoring, as a part of methodology development for BSC cover evaluation for ground-based and remotely-sensed methods, are considered in this chapter. For this purpose, initially background information of the study area is presented. In the second stage, using different criteria such as including one permanent watering point for each paddock and the length of 4 km for the main transect establishment for study paddocks selection are considered. In the third stage, a pilot project for comparison of BSC monitoring was considered to select a more suitable method of data collection for ground-truthing of stratified units in the selected paddocks, data collection for BSC classification and BSC cover data collection for variance analysis in Chapter 4. Then the concepts of where to measure in rangeland monitoring, stratification for defining homogeneous landscapes based on the selected paddocks are considered. Distances and locations of samples in each paddock according to the stratified maps in each paddock are selected and the method of data collection for BSC monitoring is descried in the next section. Landscape and site characteristics of the sampling locations are considered mostly by collecting soil and landform data. Finally, BSC group classification is considered to define suitable BSC groups for ground-data collection and spectral analysis.

3-1. Introduction

Spatial distribution of biophysical indicators can be affected by both ecological and management factors. In rangeland monitoring the aim is to measure management or human-induced effects on biophysical indicators which include BSC. They are diverse in the scale of centimetres under the effects of ecological and management factors (Eldridge, 2001) and there is no well-established framework for monitoring these diverse organisms. Thus, prior to cover variance analysis of spatial change of BSC in the framework of piospheres (Ch. 4), it is necessary to consider issues such as suitable method selection, stratification and BSC group classification to define a suitable framework for monitoring of these divers organisms. This chapter initially prepared general background information and described the study paddocks selection process. In the second stage, the chapter's aims were to explain the selection of a suitable method for data collection; stratification of landscape heterogeneity prior to BSC data collection to separate natural and trampling-induced variations in BSC cover; defining sampling locations; defining a proper sampling strategy for data collection; and finally classifying BSC components in appropriate groups for defining a framework of BSC cover variance analysis.

3-2. Background Information

As described in Section 1-18, a study area was selected at Middleback Field Centre (MFC) in a chenopod shrubland community (Figures 1-1 & 2-1). In this section, general characteristics such as climate components, geology, topography, physiography, soil, vascular plants and BSC are reviewed to gain more understanding about the study area.

3-2-1. Climate Characteristics at MFC

Climate and weather data were obtained from three rainfall stations and one synoptic station (the closest station to the MFC). In this chapter, analyses of data from the MFC and Whyalla stations are presented, and Iron Knob and Roopena stations' data are presented in Appendix E.

3-2-1-1. Long-term Rainfall Pattern in the MFC-Whyalla Region

Long -term rainfall patterns at Whyalla and the study area are similar (Figure 3-1a-b), however the rainfall means are different. The Whyalla station has a mean of 279 mm, and MFC 240 mm mean rainfall. By comparison of yearly rainfall data with the calculated mean rainfall, most years experience below average rainfall (nearly 64% below the mean rainfall at MFC and at the Whyalla station 59%) so extended dryer than average periods are common.

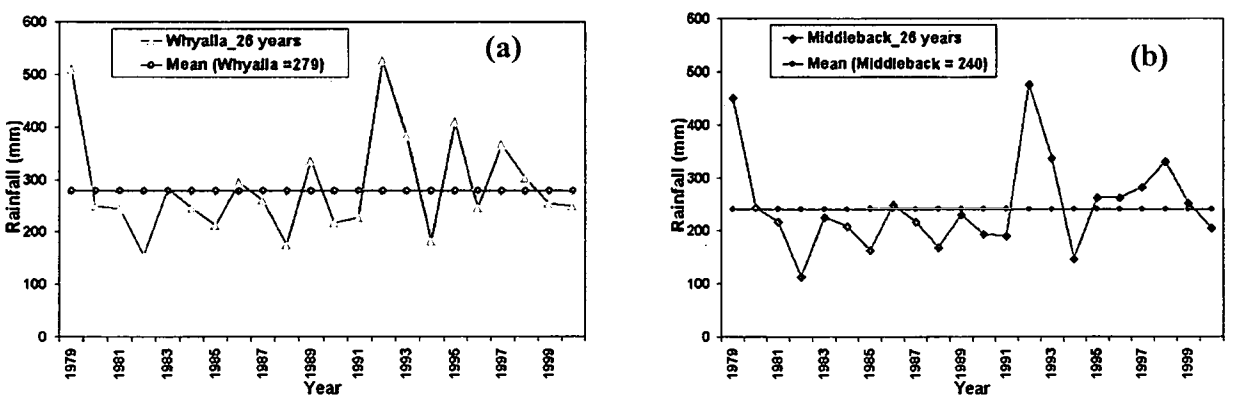

Figure 3-1. Long-term rainfall of the study area over 26 years from 1979 to 2004: a) Whyalla station and b) MFC

3-2-1-2. Rainfall During the Study Period

Daily rainfall of the study area for Whyalla and MFC recording stations during the study period (2003 and 2004) is presented in Figure 3-2a-d. The Bureau of Meteorology records rainfall data at 9 am each day, but the MFC data are usually recorded at night, a day before the recorded data at the Whyalla station. Thus, there is almost a day's difference for recorded data between the MFC and Whyalla station. Secondly, the number of rainy days is higher at Whyalla than at the MFC. For example in 2003, the number of rainy days in Whyalla was 88 events versus 37 events at MFC. In 2004 the number of rainy days in Whyalla was 95 and at MFC 32. This is partly

because at the MFC rainfall amounts of less than 1 mm had not been recorded. This is important from a perspective of remote sensing research, because if an image is selected after nearly 1 mm rainfall and presumed to be a dry image, then the results can be completely different from the real dry situation. The rainfall during 2003 at MFC of 221 mm was close to the mean rainfall of the study area, whereas 2004 with 147 mm was considerably dryer than average. Likewise, during the study period, the Whyalla station recorded 266.4 mm for 2003, which was close to the mean, and 157.3 mm rainfall for 2004 which was considerably lower than the mean.

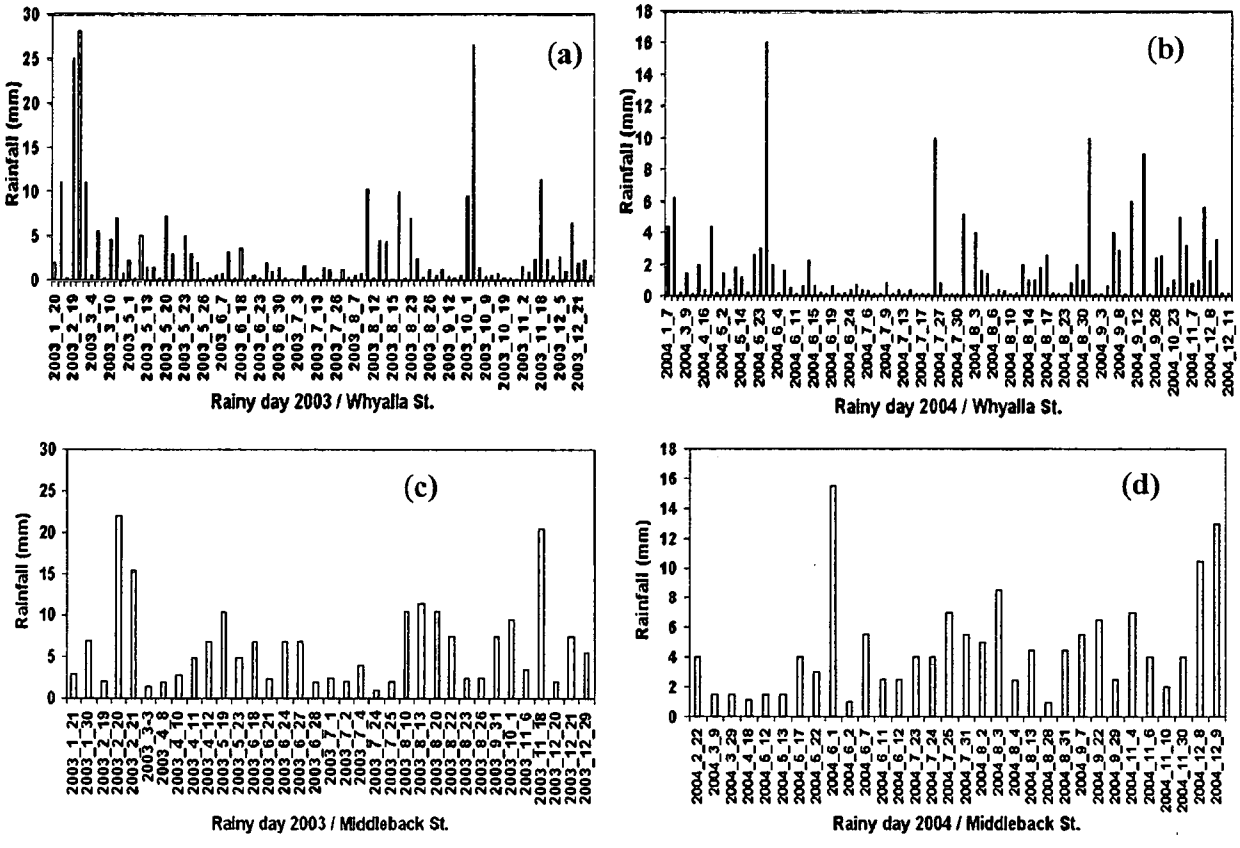

Figure 3-2. Dates of rainy days and amounts of rain during the study period for: a) Whyalla year 2003; b) Whyalla year 2004; c) MFC year 2003, and d) MFC year 2004

3-2-1-3. Long-term Temperature Pattern in the MFC-Whyalla Region

The long-term mean monthly temperature patterns (20 years of recorded temperature data at the Whyalla station) of each month are shown in Figure 3-3 for the Whyalla region (the only close station with a temperature record to the MFC). The mean monthly maximum temperature ranges from 43.4°C in January to 22.1°C in July. The mean monthly minimum temperature ranges from 12.1°C in January to -0.3°C in July (Figure 3-3). The highest temperature recorded in the 20 year period was 47.1°C (in January), whilst the lowest was -4.2°C (in October) (Figure 3-3).

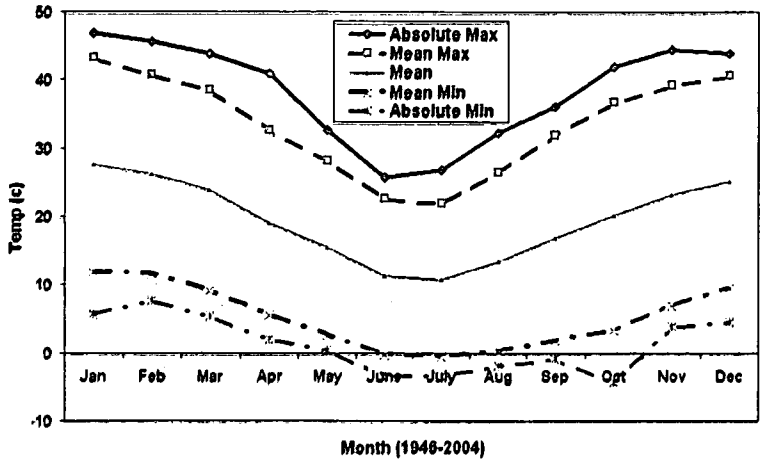

Figure 3-3. Temperature patterns of the Whyalla station for 20 years (1946-2004)

3-2-1-4. Temperature During the Study Period

Mean monthly temperatures at Whyalla for the years 2003 and 2004 are presented in Figure 3-4a & b. The mean monthly maximum temperature for 2003 ranged from 32.3°C in January to 17.5°C in July. The mean monthly minimum temperature ranged from 18.5°C in January to 5°C in July (Figure 3-4a). The highest temperature for 2003 was 47.1°C in January, whilst the lowest was - 0.4°C in August (Figure 3-4a). The mean monthly maximum temperature for 2004 ranged from 32.6°C in February to 16.4°C in July. The mean monthly minimum temperature ranged from 18.7°C in January to 5.3°C in July (Figure 3-4b). The highest temperature for 2004 was 45.9°C in February, whilst the lowest was -0.8°C in July. The data reveal definite annual patterns. This is important, particularly for the modelling of BSC detection, when considering moisture stability and dehydration after a rainfall pulse (Chs. 6 & 7). See Appendix E for more information about weather / climate data.

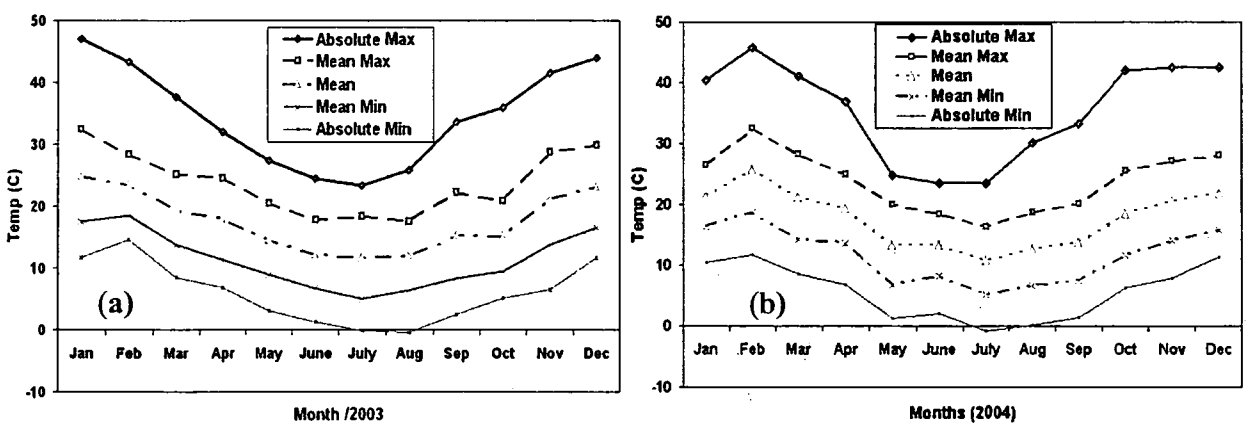

Figure 3-4. Temperature patterns at the Whyalla station during a) 2003 and b) 2004

3-2-2. Geology, Topography and Physiography at MFC

Much of the structural geology of the study area is characterized by fluvial and aeolian deposits of late Tertiary and Quaternary origin (Laut *et al.*, 1977; Johns, 1985). These have given rise to

low and gently undulating topography, characterized by a recurring system of inter fluvial slopes, plains, washes and basins (Laut *et al.*, 1977; Johns, 1985). The main exception to this is the Middleback Range, which is a low set of hills on the western edge of the study area (Figure 3-5). Isolated hills also occur on Roopena station. Elevation rises gradually from sea level at Spencer Gulf in the east to a maximum of 390 m in the Middleback Ranges in the west (Figure 3-5). These gentle undulating plains create varying habitats for BSC distribution. Topographic maps of these rangelands are only available with 10 m contours. A Digital Elevation Model (DEM) was constructed using these contours and associated spot heights (DEHAA, 2004) and the results are presented in Figure 3-5. Drainage enforcement was applied but streams were not used as an input due to their poor definitions and lack of continuity, with attempts to use streams leading to spurious results. Thus only spot heights and contours were utilized for DEM mapping. In the final stage stream lines were used to check the visual accuracy of the DEM produced.

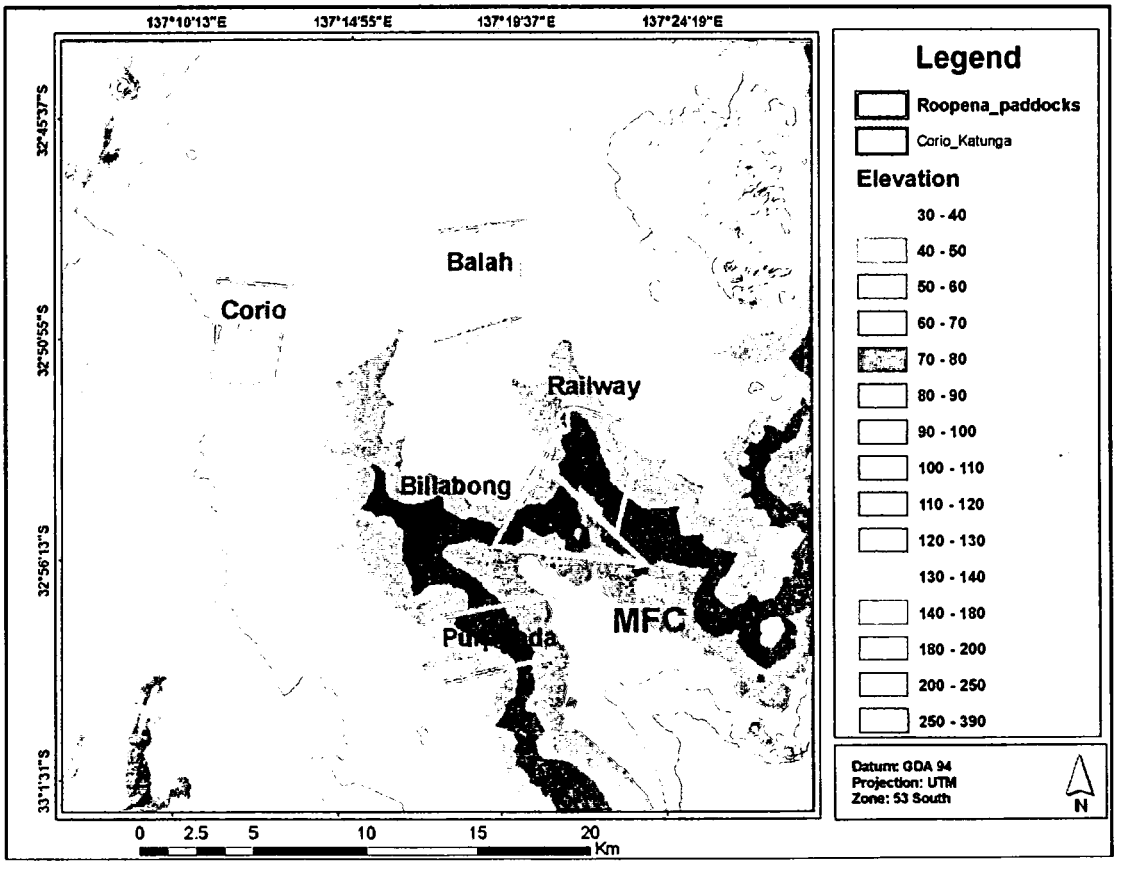

Figure 3-5. Digital Elevation Model (DEM) at MFC

A slope map was also extracted from the DEM and is presented in Figure 3-6. Both DEM and slope maps were produced using ArcGIS (ESRI, 2004) and the TIN (Triangular Irregular Network) algorithm. Neither the DEM nor the slope map depict the landscape details required at the paddock level, which requires a vertical precision of 1 to 2 m and horizontal precision of 5 to 10 m. Consequently, field-based data collection was necessary to describe the landscape

heterogeneity during the site selection stage. See Section 3-9-1 for landscape and site characterization.

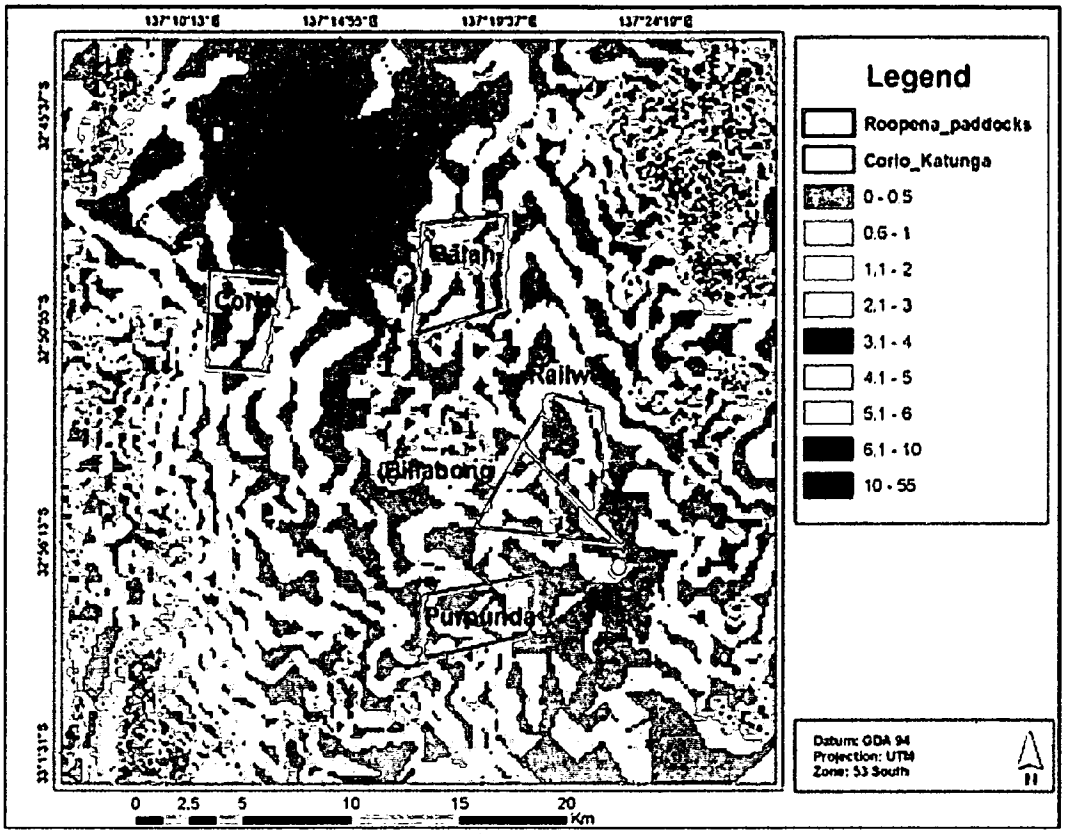

Figure 3-6. Slope map (%) of the study area

3-2-3. Soil at MFC

The soils are mainly dark reddish-brown calcareous earths (GC 1.12), which have accumulated to variable depths, usually less than 50 cm (Northcote, 1968; Wright, 1985). The texture change in the profile is gradual with sand to clay-loam at the surface, with the clay fraction increasing with depth, and a marked layer of calcium carbonate nodules at depths of 20-50 cm. Poorly drained crusty red duplex soils (Dr 1.43) are a feature of the basins and washes and are relatively saline (Wright, 1985). The pH is alkaline, and nutrient availability is low (Northcote, 1968). The soils are characterized by a surface cover of BSC and may have a pavement of gravels, pebbles or stones (Wright, 1985). The soils of the study area are often powdery and loose and prone to erosion when the vegetation or BSC are destroyed because the lighter and often more sandy topsoil is easily removed by wind and water action (Wright, 1985).

BSC are strongly influenced by changes in grain-size fraction, clay content, pH, soil nutrients, surface condition and patch occurrence at the micro-site level (Scott, 1982; Howarth, 1983; Eldridge, 2001).

3-2-4. Vascular Plants and BSC at the Study Area

Reid (1984) and Tynan (1995) stated that the vegetation at MFC is predominantly chenopod shrubland and woodland. They recorded three main perennial associations at MFC including "Chenopod Low Open-shrubland", "Western Myall Low Open-woodland" and "Black Oak Low Woodland". Annuals also have a high percentage of cover of vegetation communities at MFC (Nicolson, 1985; Facelli & Temby, 2002). Lichens and mosses are the major non-vascular plants at MFC with a dominance of lichens (Rogers, 1970; Rogers & Lange, 1971; Howarth, 1983).

3-3. Study Paddock Selection

The paddock on a sheep or cattle station is the basic unit of management in rangelands and any research or monitoring should aim to provide information at this level (Wilson *et al.*, 1984). The grazing pressure on plant communities with the same overall stocking rate is not equal in different parts of the paddock (Friedel, 1994). For example, in some cases 70% of sheep grazing time is spent in less than 12% of a paddock (Friedel, 1994), resulting in over use of that particular portion, despite an overall conservative stocking rate (Lange *et al.*, 1984). Because of high site variability rangeland ecologists need to be able to explore spatial relationships of many species over many environmental features in relation to grazing effects and it is not adequate to monitor a single point in the landscape (Friedel, 1990). Instead it is better to monitor a series of points (Tongway, 1989). Moreover, sites that are unreplicated or pseudo-replicated may result in erroneous conclusions (Hurlbert 1984). Moreover, MFC paddocks (Lange *et al.*, 1984) usually have more than one water point in which case there will be overlapping piospheres. This study aimed to select paddocks with one watering point so as to best investigate piosphere effects on BSC. To overcome these issues this study was conducted at five replicate paddocks including Balah, Billabong, Corio, Purpunda and Railway (Figure 3-7), all with a similar grazing history, except for Corio which had higher stocking rates of sheep before 1987 (Pers. comm. Nicolson family 2004). Summarized characteristics of the selected paddocks are presented in Table 3-1.

3-4. Ground-based Methods Considerations for BSC Data Collection

As mentioned in Section 1-10, three commonly used methods have been employed for collection of BSC cover data: quadrat, line-intercept and line point-intercept methods (Arzani & King, 1994; O'Neill, 1994a; Kaltenecker, 1997; Eldridge & Koen, 1998). Researchers have chosen one or other of these methods according to their ecological assumptions (knowledge-based). Alternatively, methods have become standard for a particular eco-region because subsequent researchers have followed the same methods as the first researcher in that region. This section

compares these methods to select a more suitable method for the chenopod shrubland communities at MFC.

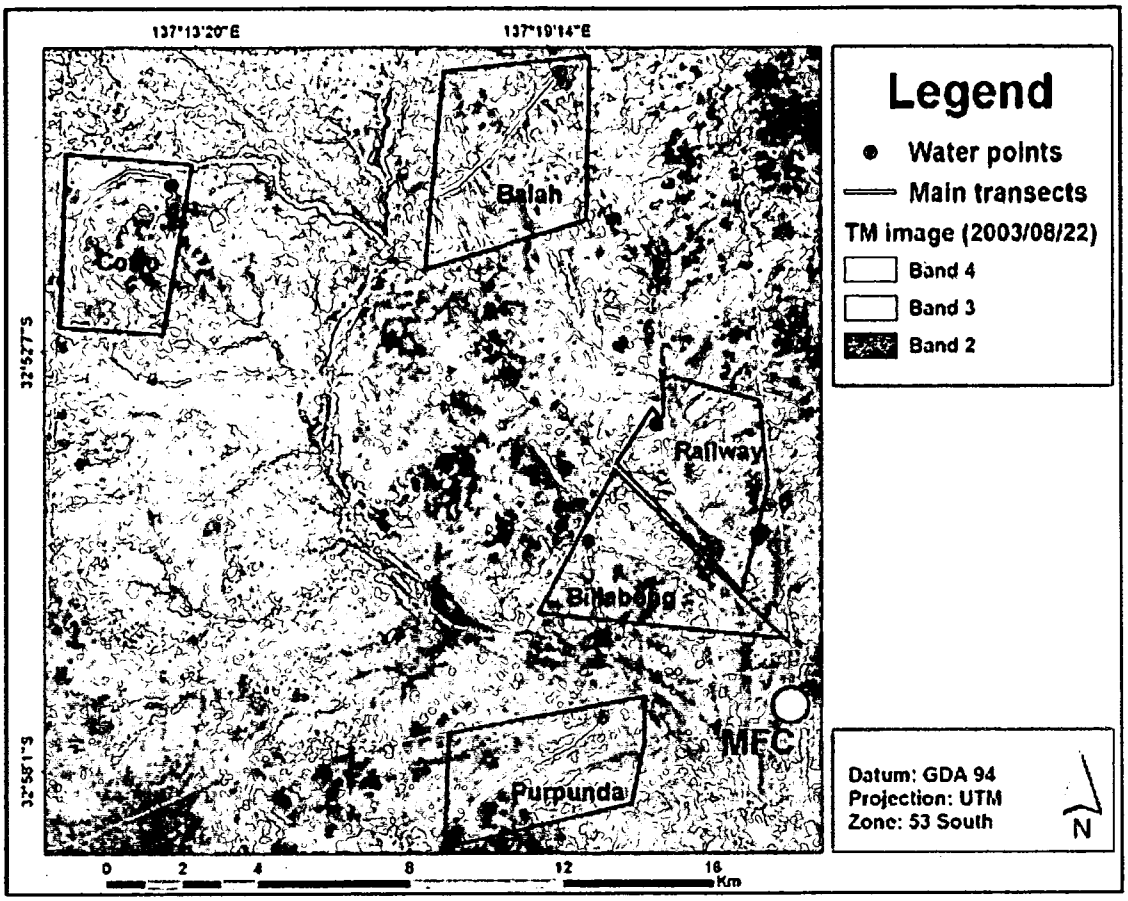

Figure 3-7. A view of the study paddocks, size, shape, location of water points and main sampling transects.

Table 3-1. Characteristics of the selected paddocks (Pers. comm. Nicolson family 2004)

Paddock	Area (km^2)	Number of sheep	Water point	Fencing	Additional Description
Balah	18.4	250	1963 + seasonal dam	1966	
Billabong	13.0	150-180	1938 + seasonal dam	1966	This paddock in late 2004 was divided into two paddocks
Corio	13.3	250-300	1989	1945	Property purchased by Nicolson family in 1987
Purpunda	14.4	250	1964	1966	
Railway	12.8	150 to 180	1938 + seasonal dam	1945	Occasionally up to 1,000 sheep are held here for several weeks prior to shearing

3-4-1. Some Considerations in the Assessment of Various Methods to Select a Suitable Method

Reliable data are of utmost importance for obtaining interpretable results from a study (Jongman *et al.*, 1987). Identifying an appropriate sampling technique first requires the identification of the proper land cover characteristics or attributes to measure (USAEC, 1999). This study aimed to

measure BSC cover. Because BSC vary at the scale of down to 1 cm, methods used for vascular plants may not be appropriate. Thus a proper sampling strategy and its relation with objects and methods of analysis is an important step in developing a methodology for the suitability of BSC cover as an indicator of rangeland condition. An important issue in assessing the usefulness of various methods of cover data collection, especially for BSC, is that actual cover can never realistically be determined for a site. The common procedure for evaluating cover data collection methods is to make repeated measurements and compare variation about the central mean or median of the data. In these situations, the usefulness of a method can only be evaluated by its robustness, which is determined by assessing the repeatability of results for a site among different methods (USAEC, 1999). Other issues such as time and labour-intensity are also important (Bonham, 1989). The method chosen is usually the one that yields the lowest statistical variation (smallest standard error and narrowest confidence interval around the mean) for a given amount of effort or money (Hanley, 1978; Bonham, 1989; USAEC, 1999).

3-4-2. Site Selection for Pilot Study Comparing Data Collection Methods

The Railway paddock (Figure 3-7) was selected for this pilot study. A site was located at 2800 m from the water point, with a relatively homogeneous pattern in terms of vascular and non-vascular plants, slope and soil. The vascular plant community is dominated by *Maireana pyramidata*, *Atriplex vesicaria* and *Maireana sedifolia*, with a typical BSC community including most major BSC components at MFC except for the absence of few Leafy Lichens such as *Xanthoparmelia convoluta, Neofuscelia* spp. and *Cyanobacterium* spp; See Section 3-10 for BSC classification.

3-4-3. Sampling Design for Comparing Data Collection Methods

The sampling unit in this pilot study was the individual transect or 10 small plots as a one "sample unit". Transects and plots were established in relatively homogeneous locations. On the selected site, five **(A, B, C, D** and **E)** 100 m parallel lines at 1 m distance to each other (Figure 3-8) were established. All lines were wetted before sampling for data collection. All five lines were used to produce five replications for each method to be trialled.

3-4-3-1. Line-Intercept Method

Two types of line-intercept methods were trialled:

100 m Whole Line Transect (Benchmark)

In order to achieve as accurate a benchmark for BSC cover as possible, a Line-Intercept Method with a 100 m (LIM100m-whole line) (Line C/ Figure 3-8) was used to collect all physical (i.e.

soil and stone), biotic (i.e. annuals, perennials and BSC) and litter. These data were assumed to characterize the cover pattern as accurately as possible, enabling various methods to be compared. The percentage cover of each component was calculated as:

$$\text{Percentage canopy cover} = (100 \times \text{Total intercept length of a species}) / \text{Total length of transect(s)} \quad \text{equation 3-1}$$

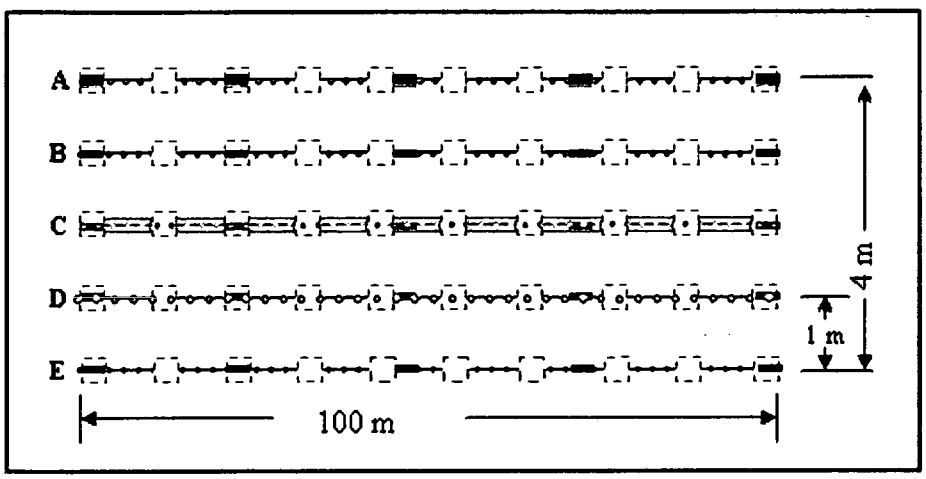

Figure 3-8. A schematic view of the three sampling methods: Line-Intercept Method with two sub-methods (Line-Intercept Method over 100 m using 2 m intervals"LIM100m" / with five replications on the defined lines / A,B,C,D & E and Line-Intercept Method-whole line using a single 100 m interval "LIM100m_whole line" – Benchmark / Line C); Line Point Intercept Method "LPIM100m" (with five replications on the defined lines / A,B,C,D & E); and Quadrat Method with 10 plots "QM10p" (with five replications on the defined lines / A,B,C,D & E)

100 m Line Transect

A 100 m with 2 m in each 20 m intervals line transect for BSC monitoring has rarely been used (Johansen *et al.*, 1984) and mostly 10 to 50 m transects are recommended (Kaltenecker *et al.*, 1999; Ponzetti & McCune, 2000; Rosentreter & Eldridge, 2002). For this study a Line-Intercept Method with a 100 m (LIM100m) length transect was established as a representative of the line-intercept method (Figure 3-8 & Table 3-2). Five replicates were carried out at each of the defined transects (**A**, **B**, **C**, **D** and **E**) (Figure 3-8). BSC and bare ground cover were taken, and expressed as simple proportions (Table 3-2). The procedure for converting measured data to the cover of each component was according to equation 3-1.

3-4-3-2. Line Point Intercept Method

Previous literature reports low value for this method for BSC estimation, particularly in Australia (Rogers & Lange, 1971; Rogers, 1972; Eldridge, 1994, 1996c; Eldridge & Koen, 1998; Eldridge, 1999). This thesis took this method into account during the pilot study to gain an estimation of its usefulness in comparison with both line-intercept and quadrat methods in the small project. In

this pilot study, by considering Australian studies (Crocker & Tiver, 1948; Arzani & King, 1994) a Line Point Intercept Method with a 100 m (LPIM100m) transect length was established on the defined site as the representative of the point intercept method. All five lines (**A, B, C, D** and **E**) were used for "LPIM100m" with a point at each 20 cm (Figure 3-8 & Table 3-2). The procedure of converting measured data to the cover of each component was conducted according to equation 3-2.

Percentage canopy cover = (100 × Total point intercept of a species / Total number of points) equation 3-2

Table 3-2. Characteristics of the employed methods

Methods		Transect length and plot number	Acronym	BSC measurement in each transect	Bare ground measurement	Other components measurement	Number of transects / plot units
Line-intercept	100 m	100 m	LIM100m	5 × 2 m intervals [1]	5 × 2 m intervals[1]	Whole line	5
	Whole line	100 m	LIM100m_Whole	Whole line	Whole line	Whole line	1
Line point intercept		100 m	LPIM100m	Each 20 cm	Each 20 cm	Each 20 cm	5
Quadrat		10 (25 ×25 cm)	QM10p	Whole plot / on the 0.0025 m^2 level	Whole plot / on the 0.0025 m^2 level	Whole plot / on the 0.0025 m^2 level	5

[1] BSC and bare ground were measured on 5 × 2 m intervals individually, and in the rest of the line BSC and bare soil (BSC + Bare ground) were measured jointly. In the second step, calculated BSC and bare soil percentage cover were modified to the collected data from whole line by simple proportion.

3-4-3-1. Quadrat Method

Eldridge and Tozer (1995), have concluded that 10 plots is a number suitable for sampling lichens on heterogeneous semi-arid landscapes. A 10 (25 × 25 cm) Quadrat Method (QM10p) was selected on the defined transect lines (replicated five times on lines **A, B, C, D** and **E**) (Figure 3-8 & Table 3-2). On each line 10 plots were collected and considered as one sampling unit. Each quadrat was divided by wire into 25 separate sub-quadrats. Cover of vascular and non-vascular plants was visually estimated in each sub-quadrat.

3-4-4. Data Analysis

A comparison of the accuracy of two or more methods for sample collection when there is no exact indication of the real population is difficult (Hanley, 1978; Arzani & King, 1994; Stohlgren *et al.*, 1998; USAEC, 1999). Nevertheless, methods are often statistically compared to

assess repeatability, by comparing means, modes, standard deviation, variance, confidence intervals and standard error of repeated measurements. Most of these comparisons have concentrated on the central mean or median of collected data. A robust method is defined as one with low variability of descriptive statistics by repeated measurement of sampling in the same place with the same photosynthetic components and achieving a close value to the reference (benchmark / Line C). The concept was: if a sampling method has the lowest variation for different mean-based statistical analysis with the closest value to the reference line, it is more robust than the others.

The Coefficient Of Variation (COV) of a sample is a unit-less, relative measure that provides an estimate of the sample variability relative to the sample mean (USAEC, 1999). It is referred to as a relative measure of dispersion. This measurement may be calculated only for ratio-scale or proportional data. The COV is defined as:

$$COV = S / \overline{X} \qquad \text{equation 3-3}$$

where S = standard deviation, and $\overline{X}$ = sample mean

The COV is especially useful when comparing the results of different survey designs and data collection methods (USAEC, 1999). The approach which produces the lowest COV is desirable from a statistical standpoint. It is recognized that COV should not be the sole basis for selecting a method; issues such as sampling errors (e.g. bias), and cost should also be considered (USAEC, 1999). Descriptive analyses in this chapter were conducted using SPSS v. 12 (2004).

3-4-5. Comparison of Methods

A profile plot comparing the cover results of various ground cover components yielded by the various sampling methods to be compared (LIM100m", "LPIM100m" and "QM10p") with an assumed high-accuracy measurement ("LIM100m-Whole line") is shown in Figure 3-9 and Table 3-3. As can be seen from the graph, mean percentage cover yielded by each method for bare ground, litter, vascular plants, total BSC, lichens and mosses is close in value to the reference data (Line C with whole line collection). However, regardless of these similarities, the standard errors are considerable particularly when using the "QM10p" method. According to Figure 3-9 and Table 3-3, variations between samples in "LIM100m" tend to be lower than other methods for most ground-cover components. Skewness and kurtosis tests, and confidence intervals (Table 3-3) for this method also show that it has the lowest overall amount of deviation from the mean (Table 3-3). "LPIM100m" has the lowest variation after "LIM100m". Finally, "QM10p" had the overall highest variation for all types of ground cover. Table 3-3 illustrates the use of coefficient of variation (COV) to compare the three field methods for estimating the mean of total BSC percentage cover. Once again, the "LIM100m" has the lowest COV, followed by

the "LPIM100m" and "QM10p". Overall, from this pilot study, it seems that a 100 m line-intercept method with 5 × 2 m intervals is most suitable for collecting ground-cover data in relatively homogeneous chenopod shrubland at MFC.

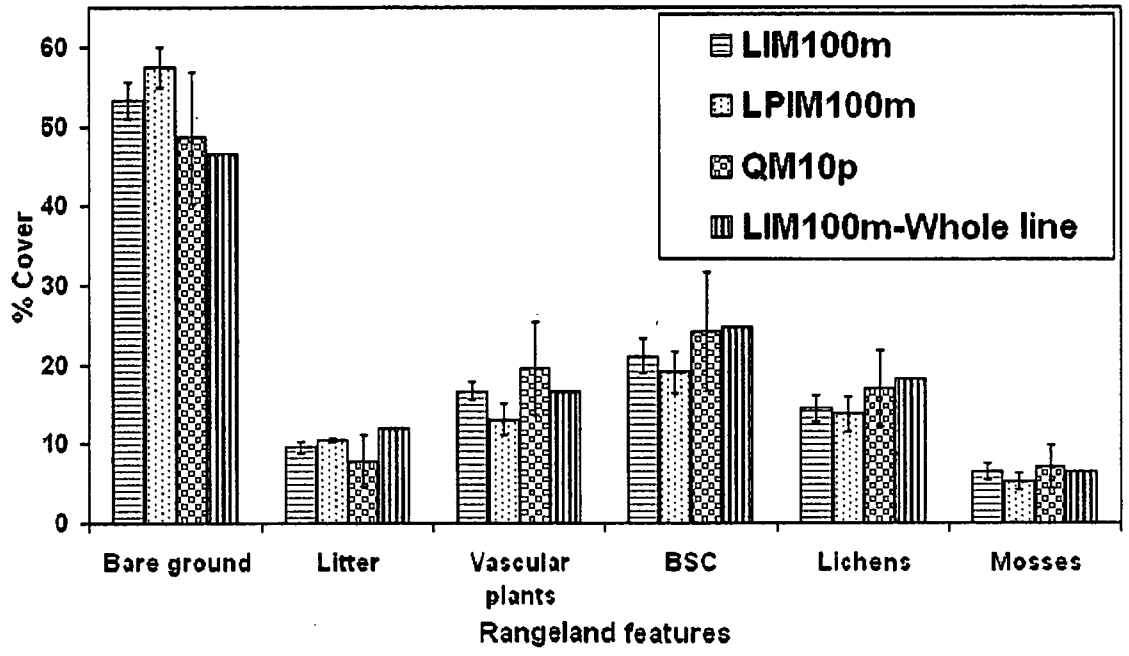

Figure 3-9. Mean percentage cover (± standard error) for major ground-cover elements for three methods: Line-Intercept Method with two sub-methods (Line-Intercept Method with 100 m "LIM100m" and Line-Intercept Method-whole line with 100 m "LIM100m_whole line"); Line Point Intercept Method "LPIM100m"; and Quadrat Method with 10 plot "QM10p". "LIM100m-whole line", the reference data, was collected only at one transect, and therefore no error could be derived: it is used for comparison with the other methods only.

Table 3-3. Total BSC: descriptive statistics and coefficient of variation (COV) for three methods (Line-Intercept Method with two sub-methods; Line Point Intercept Method "LPIM100m"; and Quadrat Method with 10 plots "QM10p"). "LIM100m-whole line" was collected only at one transect, and is not presented in this table.

Methods	N	Mean		Std.	Variance	95% Confidence Interval for Mean		Skewness		Kurtosis		COV
	Statistic	Statistic	Std. Error	Statistic	Statistic	Lower Bound	Upper Bound	Statistic	Std. Error	Statistic	Std. Error	
LIM100m	5	21.0660	2.27014	5.07619	25.768	14.7631	27.3689	.688	.913	-.640	2.000	0.24
LPIM100m	5	19.0280	2.64912	5.92362	35.089	11.6729	26.3831	-1.409	.913	2.238	2.000	0.31
QM10p	5	24.1600	7.37602	16.4932	272.028	3.6809	44.6391	.565	.913	-3.051	2.000	0.68

3-5. Stratification of the Study Paddocks

As pointed out in Section 1-11, a number of studies have emphasized that stratification can improve accuracy and precision of spatial sample collection in ground-based and remotely-sensed methods (Graetz & Ludwig, 1978; Moran *et al.*, 1997; Bastin *et al.*, 1998; Friedel *et al.*, 2000; Brook *et al.*, 2001; Wright *et al.*, 2003; Edwards *et al.*, 2005). Most attempts at

stratification have taken into account soil type, vegetation or both (Graetz & Ludwig, 1978; Ludwig & Tongway, 1992). However, Belnap *et al.* (2001b) and Rosentreter and Eldridge (2002) have emphasized that stratification of the landscape is necessary where the landscape is composed of a number of homogeneous land units. To my knowledge there has been little use of landscape stratification prior to BSC cover evaluation in Australia. In remotely –sensed studies, Bastin *et al.*(1998) while implementing a grazing gradient study concluded that paddocks generally contain several landscape / soil types (Low *et al.*, 1981), and these must be identified and mapped before using grazing gradient methods. Brook *et al.* (2001) also concluded that landscape stratification is essential for obtaining meaningful results using the grazing gradient method and also that the available regional-scale land system mapping is too coarse to separate heterogeneity in some land systems. They reported that, given the time constraints of the project, a classification of land types using satellite imagery was not possible. For updating and improving the existing land system mapping Brook *et al.* (2001) used digital geology data, claiming that the geology maps provided more detailed stratification than existing land system maps for their objectives. Consequently, they updated the land system maps by intersecting the digital geology with the land system polygons and merged geology units into major land types on the basis of their vegetation composition and soil type. They also concluded that this final map layer, although not ideal for grazing gradient analysis, better represented the grazing preference of cattle for different communities.

3-5-1. Existing Stratified Resources at MFC

Laut *et al.* (1977) have reported that the study paddocks are distributed on three upland landform units (Figure 3-10) including: 4.2 "Buckleboo", gently undulating calcrete plains with occasional quartzite or granite hills, low open woodland and mallee scrub; 4.6 "Whyalla", calcrete plain with occasional conglomerate hills and tidal flats with low open woodlands; and 4.7 "Red rock", conglomerate hills with long dissected foot-slopes, low open woodlands and chenopod understorey. The scale of the original land unit map was 1:500,000. As can be seen from Figure 3-10, the area of the study paddocks is very small in comparison with existing land units, and during pilot surveys a high variation was identified in both vascular plants and soil attributes within each paddock. This means that there is little possibility to establish stratification based on Laut *et al.* (1977) land units. There was therefore a requirement for stratification within paddocks for BSC detection.

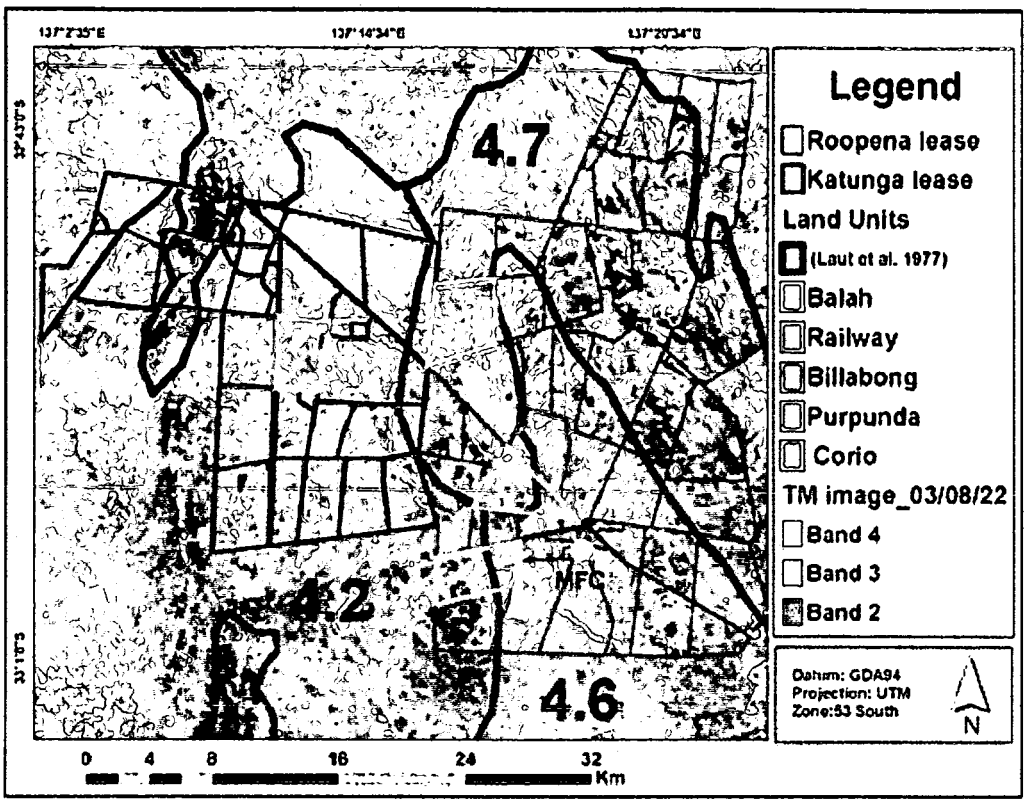

Figure 3-10. Land units (after Laut *et al.* 1977), in comparison with the study paddocks extent.

3-5-2. Stratification at Paddock Scale

Traditionally, visual interpretation of aerial photographs and remotely-sensed data have been used for stratification in rangeland monitoring (Poulton, 1975; Tueller, 1987; Tueller, 1989, 1995). In assigning each physiognomic element, the percentage cover of the dominant components such as shrubland or woodland is usually considered. A reconnaissance field visit was conducted in five paddocks prior to stratification, then visual interpretations of the Landsat images for each paddock were conducted in the laboratory for whole paddocks. When the pre-stratified units were mapped they were checked in the field (study paddocks were checked).

When classifying vegetation and soil strata, if shrub components were more than 75% of a given community it was assigned as a shrubland physiognomic group. Alternatively, if tree species were more than 75% of the community it was classified as a woodland physiognomic group. In the case in which shrubs were more than 50% and tree species were less than 50% of the community, it was assigned as a shrub- woodland community and vice-versa for others. Stratified maps of the study area are presented in Figures 3-11 to 3-15.

3-6. Main Transects

As reviewed in Section 2-7, there is no universal agreement about the length of a main sampling transect to detect changes along a piosphere gradient, but most previous researchers believe a 3

to 5 km length is suitable for sheep paddocks (Wilson *et al.*, 1992; Landsberg *et al.*, 1997). This study established a 4 km length main transect in the defined paddocks. Figure 3-7 shows the location of water points and main sampling transects. Sampling transects along a gradient are aimed as a straight line, but because of some limitations, such as road accessibility, were established as shown in Figure 3-7 and Figures 3-11 to 3-15.

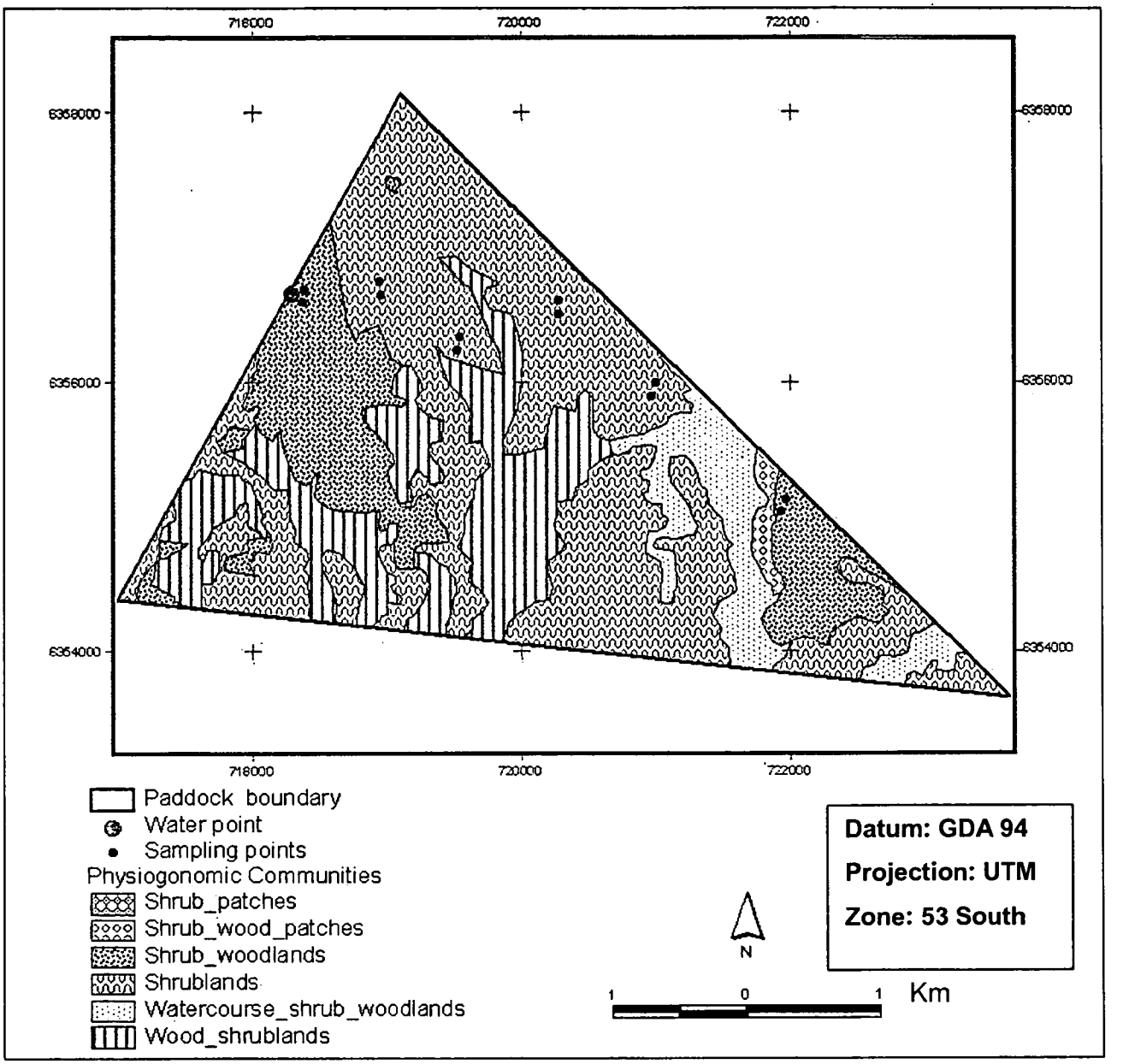

Figure 3-11. Billabong paddock, stratified resource and sampling location: dot points in each sample location show the beginning and ending of a 100 m transect, each sample location is measured from water points by the defined distances

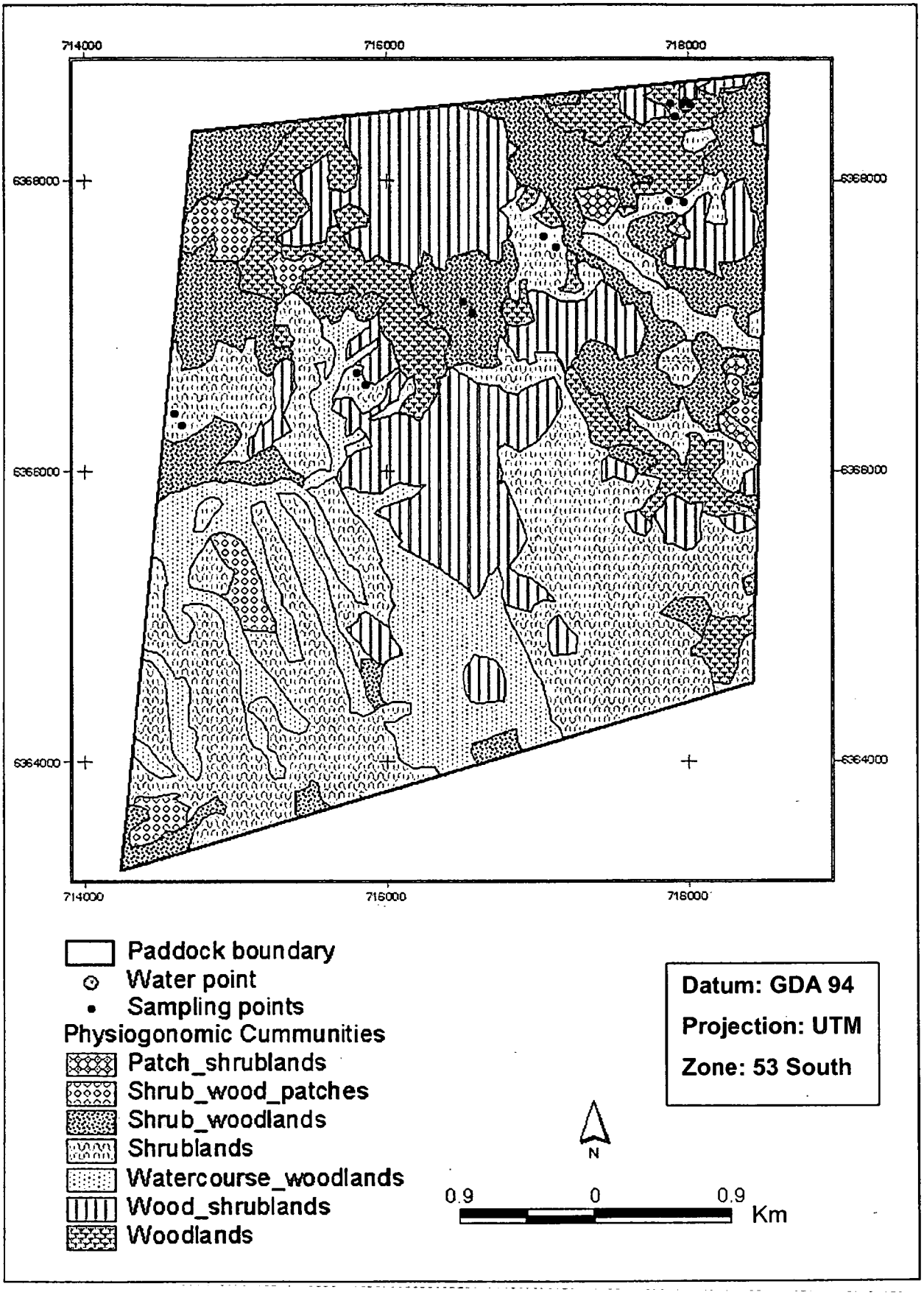

Figure 3-12. Balah paddock, stratified resource and sampling location: dot points in each sample location show the beginning and ending of a 100 m transect, each sample location is measured from water points by the defined distances

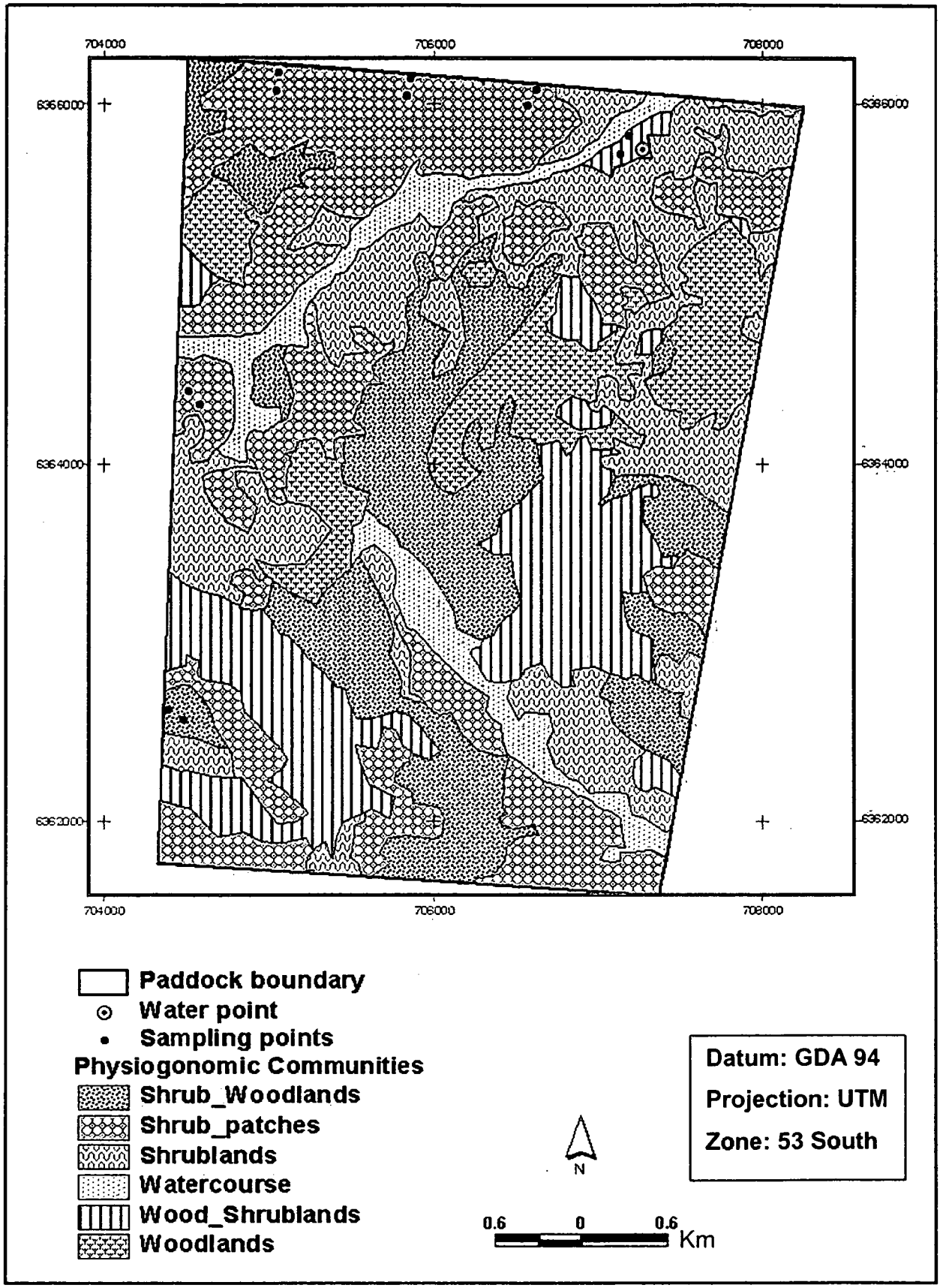

Figure 3-13. Corio paddock, stratified resource and sampling location: dot points in each sample location show the beginning and ending of a 100 m transect, each sample location is measured from water points by the defined distances

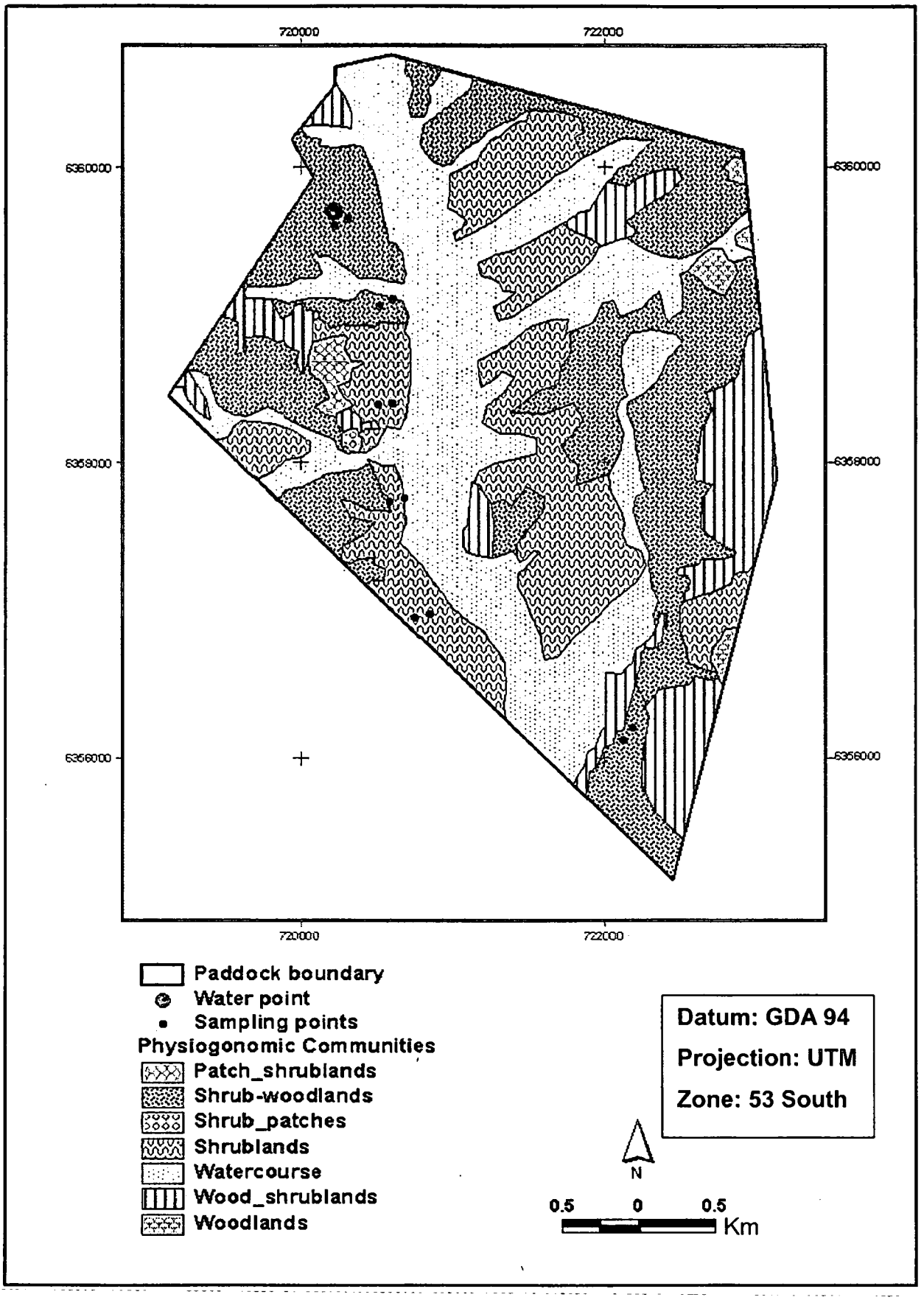

Figure 3-14. Railway paddock, stratified resource and sampling location: dot points in each sample location show the beginning and ending of a 100 m transect, each sample location is measured from water points by the defined distances

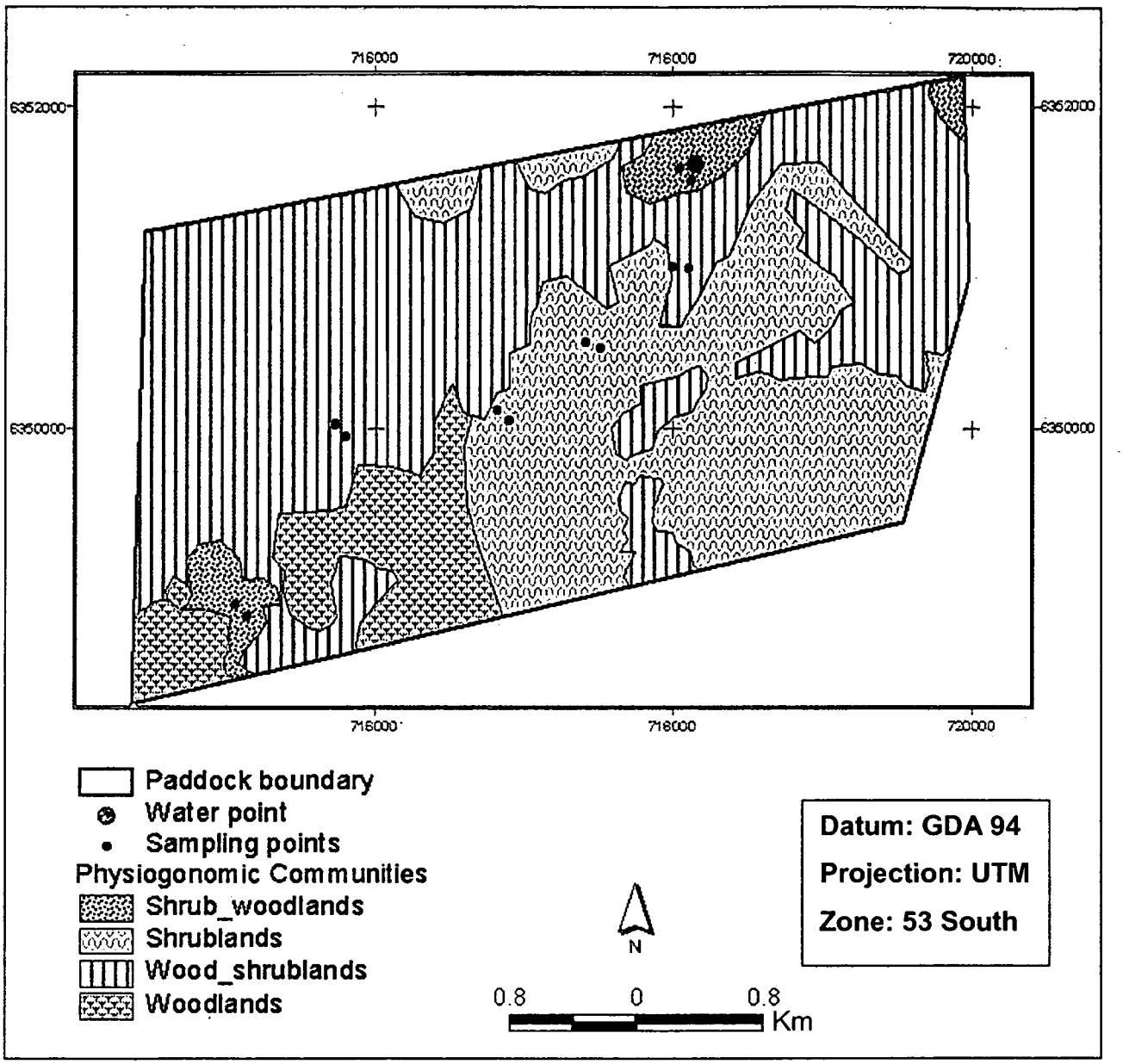

Figure 3-15. Purpunda paddock, stratified resource and sampling location: dot points in each sample location show the beginning and ending of a 100 m transect, each sample location is measured from water points by the defined distances

3-7. Selection of Sampling Distances and Locations

Rangelands are large and encompass so much spatial variability in soil, vegetation and other characteristics, it is seldom efficient to select monitoring locations at random (Smith, 1990). Generally, several replicate sets of sites are required to give an indication of how much natural variation exists between sites independent of pressures. The size, location and number of site-sets is dependent on the issues being addressed, the elements of change of interest, the extent and nature of pressures, and the variability of paddock types in the region (Landsberg *et al.*, 2003). Sampling at each monitoring location was limited to an area as uniform as possible with respect

to vegetation type, soil, slope, aspect and topographic position after stratification. As reviewed in Section 2-7, existing literature reported that there is a zone of 0-400 m from a watering-point where vegetation has been dramatically altered. This area is usually dominated by annual plants after rainfall (Graetz, 1978). From 400 m to about 1 km, there is often a zone of bush encroachment. Barker (1979) documented an increase in *Maireana pyramidata* close to the water point, a decrease in populations of *Atriplex vesicaria* near water, and no change in *Maireana sedifolia* populations over a 2 km gradient from water. The pre-defined sampling intervals on the main transects were 100, 500, 1000, 2000, 3000, and 4000 m (Figure 3-16). However, the exact distances of sites were modified from stratified maps (Figures 3-11 to 3-15) as 100, 660, 1300, 2000, 2800 and 4000 m.

In the site selection shrubland communities were chosen as a priority. If site selection in a shrubland community was not possible at the appropriate distance from water, due to unavailability or vehicle access problems, then a shrub- woodland community was chosen. If sites with a dominance of shrub components were not possible then wood-shrubland, in the first place, and woodland community, in the second place, were considered. Watercourse units, because of vegetation and soil complexity in comparison with usual shrubland communities and negative relationship with BSC distribution from the pilot study results, were avoided for site selection. Sample locations were carefully identified and recorded by a Global Positioning System (GPS) (Garmin / 12xL / ±10 m error) and data were transferred to ArcView (ESRI, 2002) by OziExplorer v.3.95.3c (Newman, 2003) to ensure that the same area is sampled subsequently and any atypical areas to be excluded were carefully defined. The photographs of the selected sample locations are presented in Appendices A-2 to A-6. Overall in five paddocks 44% of the selected sites were established on shrubland communities. A further 30%, 13%, 10% and 3% of total sites were established on shrub-woodland, shrub-patches, wood-shrubland and woodland communities respectively. Overall, 87% (44% shrubland and 43% shrub-woodland) of the selected sites were established in communities with a dominance of shrub components.

3-8. Data Collection for Ground-based and Remotely-sensed Methods

As explained in Section 3-4 a 100 m line-intercept method for collecting ground cover data in chenopod shrubland communities was found to be most suitable. As described in Section 3-4, for the defined 100 m, there needed to be a hierarchical system of sampling at each transect, because BSC were required to be measured at a much smaller scale than large vascular plants such as *Atriplex* spp. and *Maireana* spp. Thus vascular plants were recorded on the full 100 m line-

intercept and BSC were recorded on 5 × 2 m line-intercepts evenly spaced out along the 100 m transect (Figure 3-16).

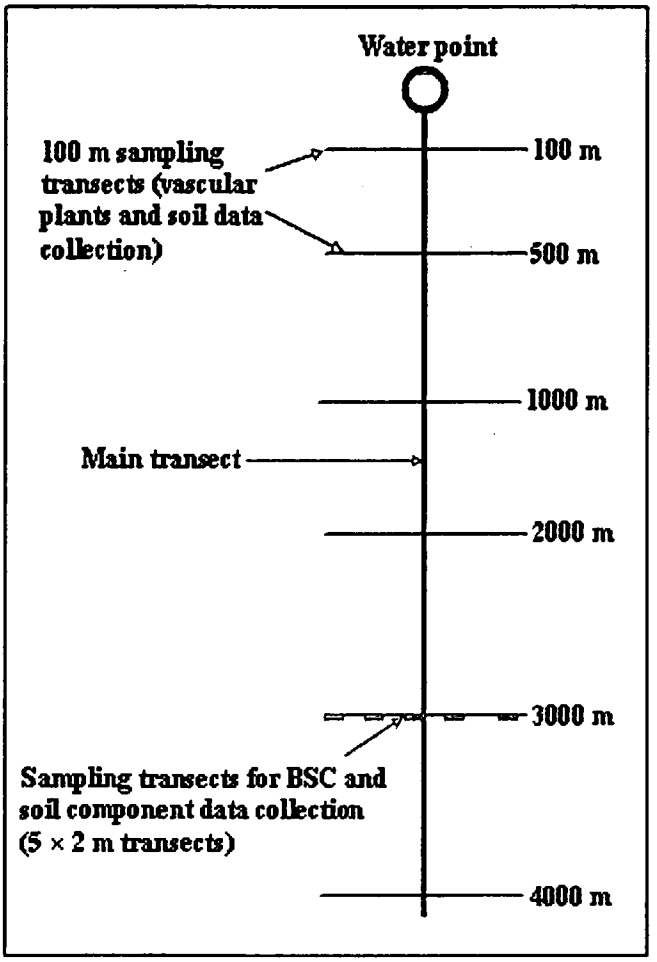

Figure 3-16. Schematic plan of the transect-based data collection on the ground showing a main transect with sampling transects at varying distances from a watering point (before stratification)

The following directions were followed for data collection:

1. A squirt bottle was used to dampen the smaller line transects with water so that all BSC could be detected, as most BSC are inconspicuous when dry.
2. Specimens of each BSC organism encountered were taken and stored in plastic (Petri dishes) for later identification and spectral collection in the laboratory. David Eldridge assisted with identification of collected species.
3. The morphological / functional type of each organism (e.g. bushy, platy, leafy cover of BSC, and herb, shrub, tree for vascular plants) was recorded.

Vascular plants were recorded on 100 m transects. BSC and soil components (soil colour and texture) were recorded on 5 × 2 m intervals and pH was measured on three out of five of the 2 m intervals (first, third and fifth intervals) along the established transects. These data were collected from each of 6 sampling transects in each paddock, resulting in a total of 30 transects.

3-9. Landscape and Site Characterization

3-9-1. Characterization of Landscapes (Landforms) on the Selected Sites

The landform classifications and slope characteristics of the 30 sites from the five paddocks are shown in Table 3-4. Slope data enables a number of site characteristics to be defined: rate of runoff (increases with slope), chronic dryness (crest of slope) and periodic ample water (closed depression) (Tongway, 1994). These classifications are important for interpretation of the BSC distribution in different sites. Landform units that were proposed by Tongway (1994) (Figure 3-17) for rangeland surface classification were used in the selection of sample locations. Units such as crest, upper slope, mid slope, lower slope, flat, closed depression and stream channel were used to classify geomorphic units. Forty seven percent of the 30 sites were located on flat landforms, 30% on mid-slopes, 20% on low slopes and 3% on crest to upper slopes. All of the sites were located on less than 1% slope (nearly 97%) except for one site at 2000 m in Balah paddock which was selected on a crest (1 – 3% slope) because of the lack of availability of a more suitable site (Table 3-4).

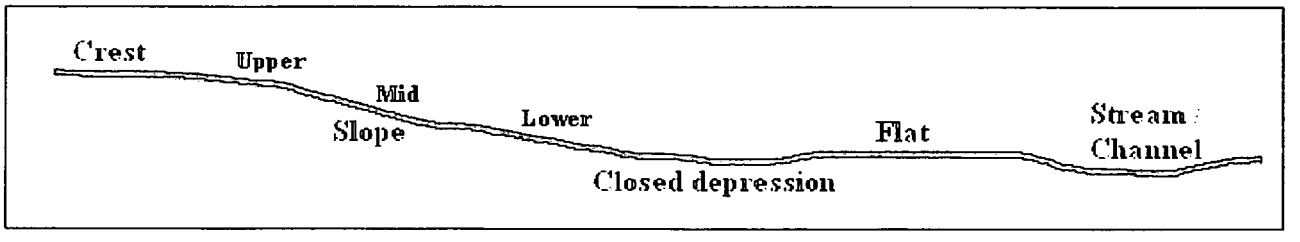

Figure 3-17. A schematic plan of different possible landforms adapted from Tongway (1994)

Table 3-4. Landform category and % slope of sampling locations

Paddocks	Distance from watering-point and landform characteristics					
	100 m	660 m	1300 m	2000 m	2800 m	4000 m
Balah	Mid slope / <1%*	Mid slope / <1%	Mid slope / <1%	Crest to upper slope / 1-3%	Mid slope / <1%	Mid slope / <1%
Billabong	Lower slope <1%	Lower slope <1%	Mid slope / <1%	Mid slope/ <1%	Mid slope / <1%	Lower slope <1%
Corio	Flat /<1%	Flat /<1%	Flat /<1%	Flat /<1%	Lower slope <1%	Mid slope/ <1%
Purpunda	Flat /<1%	Flat /<1%	Flat /<1%	Flat/<1%	Flat/<1%	Lower slope <1%
Railway	Flat /<1%	Flat /<1%	Flat /<1%	Flat/<1%	Flat /<1%	Lower slope <1%

3-9-2. Soil Physical and Chemical Characteristics of Sampling Sites

3-9-2-1. Soil Patchiness

Soil patchiness (Appendix A-7), or mode of erosion as defined by the presence of bare patches, is considered to be a factor in BSC distribution (Eldridge, 2001). During the stratification and

ground-truthing for site selection, sites with soil patchiness were defined as patch-shrubland or shrub-patches. If the percentage cover of bare patches was more than the percentage cover of biological components the site was designated as patch-shrubland, and if shrub percentage cover was more than the percentage of bare soil, the sites were designated as shrub-patch (Figures 3-11 to 3-15). Soil patchiness was not a dominant feature in the study area except in Corio paddock. Soil patches, regardless of their size, were counted along the 100 m transects. Soil patchiness distribution (frequency) is presented in Figure 3-18. Soil patches are only a common feature on six sites including: 1300 m and 2000 m in Corio, 2800 m and 4000 m in Billabong, 2800 m in Balah and 4000 m in Railway paddock.

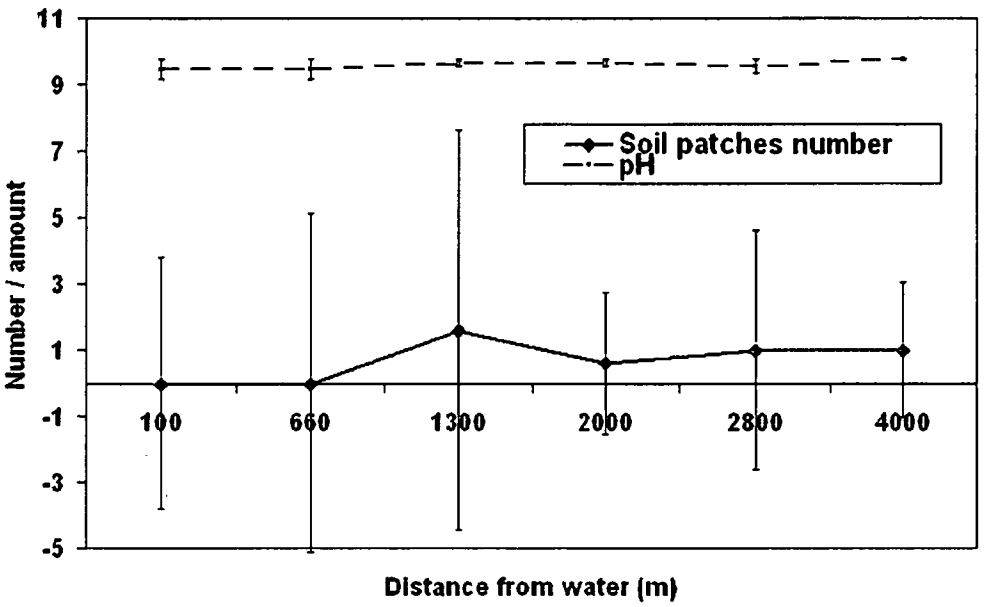

Figure 3-18. Mean soil attributes (± standard errors) on the sites of the five paddocks

3-9-2-2. Soil pH

At a continental and regional scale BSC respond to broad changes in soil chemistry, particularly pH (Downing & Selkirk, 1993; Eldridge, 2001). A few species are confined to soils with high levels of extractable calcium and high pH (Rogers, 1977). Therefore, it seems that there is a relationship between pH and the distribution of BSC communities. This study used a pH measurement kit (Inclulo Laboratories, 2004) to measure pH in three out of five 2 m intervals along the 100 m transects (by considering literature which mentioned that MFC has alkaline soil and from the pilot study results, it was concluded that 3 samples in each site was sufficient for pH measurements) and the mean of the five paddocks for each distance from water was plotted (Figure 3-18). Soils of the study area are strongly alkaline with pH usually ranging from 9.5 to 10, but occasionally varying as widely as 8 to 10.

3-9-2-3. Soil Texture

Both mosses and lichens are thought to be more common on fine-textured soils than on sands or self-mulching clays (Rogers & Lange, 1972; Rogers, 1977; Eldridge, 2001). Extensive literature in southern Australia reveals that lichens are generally restricted to loamy soils, and are absent from sandy soils and both cracking and swelling clays, while mosses tend to grow on the mounds associated with perennial shrubs (Rogers & Lange, 1972; Eldridge, 2001). A bolus technique (Northcote, 1979) using a sample of 0-5 cm diameter was used to classify soil texture in the field to one of four simplified classes (Table 3-5) at each of the defined 5 × 2 m intervals. The mean of the five measurements was used to characterise the soil texture for each 100 m transect.

Table 3-5. Simplified soil classification system modified from Tongway and Hindley (1995)

Class	Soil texture
1	Fine (heavy clay, clay, silty clay / with very slow infiltration)
2	Fine to moderate (sandy clay loam to sandy clay / slow infiltration)
3	Moderate to coarse (sandy loam to silt loam / moderate infiltration rate)
4	Coarse (sandy, sandy to sandy clay / high infiltration rate)

The results of soil texture are presented in Table 3-6. Soil texture was not entirely homogeneous at all sites. During the stratification and mapping process as described in Section 3-5 the sites with less than 50% cover of woody plants were excluded. However on the established transects, suitable sites could not always be found. For example, there were no woody plants at sites 100 m and 4000 m in Billabong paddock and site 660 m in Railway paddock (Appendix C-1). Sites with high cover of woody vegetation tended to have sandier soil texture (Figures 3-11 to 3-15 and Appendix C-1). Water points are established mostly around woodland communities because of the availability of shade for livestock, so the soil texture around watering points tends to be sand (3 out of 5 paddocks) or moderate to coarse (1 out of 5).

Table 3-6. Soil texture at the study sites

Distance from water/ m	Balah	Billabong	Corio	Purpunda	Railway
100	Coarse	Coarse	Coarse	Moderate	Moderate to coarse
660	Moderate to coarse	Moderate	Fine	Moderate to coarse	Fine to Moderate
1300	Moderate	Moderate	Moderate	Fine to Moderate	Fine to Moderate
2000	Moderate to coarse	Moderate	Fine to Moderate	Fine to Moderate	Fine to Moderate
2800	Fine to Moderate	Fine to Moderate	Fine	Moderate to coarse	Fine to Moderate
4000	Fine	Fine to Moderate	Moderate to coarse	Coarse	Fine to Moderate

Of the 13 transects with both woody and shrubby vegetation, nine had sandy soil texture, while in the shrub-dominated communities without woody species one out of 16 sites had moderate to coarse soil texture while the other 15 had fine and moderate textures. Thus it was concluded that there is a relationship between the woody plant dominance and sandy soil. By observation there is weak relationship between sandy soil and BSC distribution. Further clarification of the relationship between soil texture and BSC would require a separate study and statistical analysis.

3-9-2-3. Soil Colour

Classification of soil colour was carried out using a Munsell soil colour chart (See also Section 5-5). A mean of five point measurements of soil colour on each 100 m transect (at 0, 20, 40, 60 and 80 m) was taken to represent the colour of the soil at each site. Soil colour of the study sites is presented in Table 3-7. Colour varies between six discernable soil colours, with no obvious pattern between paddocks or distance from watering-points.

Table 3-7. Soil colour of the study sites

Munsell Soil Colour Chart	**7.5 YR, 4/4***	**7.5 YR, 5/4**	**7.5 YR, 6/4**	**7.5 YR, 5/6**	**7.5 YR, 6/6**	**7.5 YR, 7/4**
Soil Colour	**Brown to brown dark**	**Brown**	**Light brown**	**Strong brown**	**Reddish yellow**	**Pink**
Balah	100	660	1300/2000/ 2800/4000			
Billabong				100	660/1300/ 2000/2800/ 4000	
Corio	4000		660	100		1300/20 00/ 2800
Purpunda			1300	660/2000/ 4000	100	2800
Railway		4000			1300/ 2000	100/660/ 2800

*** Hue, Value/ Chroma**

3-9-3. Grazing Intensity at the Study Sites

3-9-3-1. Sheep Track Frequency

Sheep tracks are clearly marked pads of constant use (Lange, 1969; Andrew & Lange, 1986a), easily differentiated from the scraping of the surface BSC made by occasional, inter-track wanderings (Andrew & Lange, 1986a). In order to gain more insight into the accumulated grazing history of the sites, track density was assessed by recording the number of well-defined tracks crossing the sampling transects at each site. Only clearly incised tracks indicative of regular use were counted. The number of tracks at each site is presented in Figure 3-19.

According to the graph there is high fluctuation in track density from paddock to paddock, but the general pattern of tracks show the track density decreasing with distance from water.

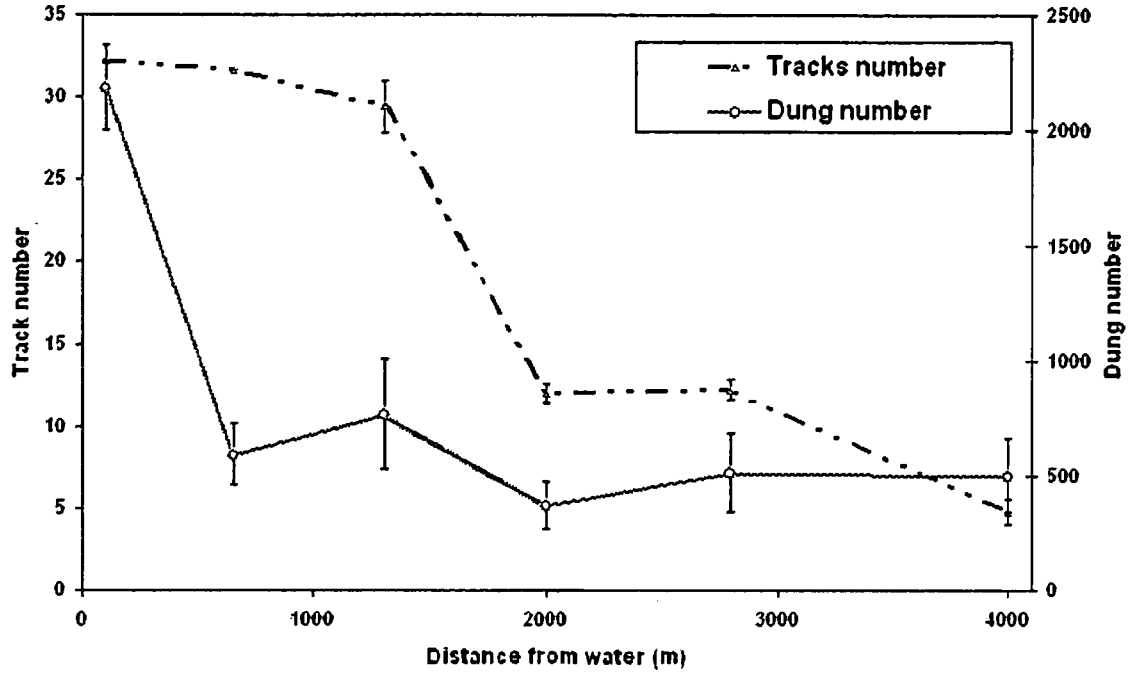

Figure 3-19. Mean values (of five paddocks) and standard errors of sheep track frequency and dung-pellet numbers against distance from watering-points.

3-9-3-2. Dung Counts

The quantity of animal dung can give an indication of the intensity of animal use (Lange, 1969). Thus, for characterisation of the grazing (trampling) gradient (Lange, 1969; Andrew, 1988) at different distances from water, sheep dung-pellets were collected along a 100 × 2 m strip transect at each site. The number of dung-pellets at each distance from water (mean of five paddocks) is presented in Figure 3-19. There are very high amounts of dung around the water points in comparison with the sites away from water.

3-10. Morphological / Functional Groups Classification

Büdel (2001) and Eldridge (2001) have reported nearly 200 BSC species for Australia (See Section 2-5-4). Each species, particularly the rarer species such as *Chondropsis semiviridis*, have a unique value as indicators of rangeland condition (Eldridge & Koen, 1998). However, from the monitoring perspective, particularly when remotely-sensed methods are to be applied, and considering that genus and species-level identification can only be made microscopically, it is important to be able to classify individual species into a smaller set of homogeneous and more easily identified field groups. As this study intended to use the classified groups for ground-based piosphere analysis and developing a remotely-sensed method of BSC detection, the groups need to be arranged so as to take colour, spectral qualities and trampling sensitivity into account.

Then, they can be used to detect trampling (grazing) pressure on the ground, and can be used as indicators during monitoring by remote sensing i.e. the groupings are not just for taxonomic purposes.

3-10-1. Morphological Groups

As mentioned in Section 1-12, BSC of arid and semi-arid ecosystems have traditionally been difficult to identify and study, even to genus and family level, with confidence in the field and laboratory studies (Eldridge & Koen, 1998; Belnap *et al.*, 2001a). There are a number of reasons for these difficulties, including taxonomic problems; lack of expert knowledge (Eldridge & Rosentreter, 1999; Belnap *et al.*, 2001a); small size; intermixing of taxa in the field; and within-species variation (Belnap *et al.*, 2001a; McIntosh, 2003). Because of these difficulties, BSC are rarely recorded during routine rangeland monitoring, particularly in ground-truthing of a remotely-sensed method, despite increased acceptance over the past decade of their importance in ecosystem processes (Harper & Marble, 1988; West, 1990; Eldridge & Greene, 1994). Any mention of BSC is usually confined to broad classes of organisms such as mosses or lichens (Cameron & Lewis, 1996; Lewis *et al.*, 2001; Fildes, 2005), or used only in passing reference. The recording of data within broad classes is often misleading or uninformative, because different BSC groups such as gel-like and leafy lichens respond differently to physical disturbance and provide different ecological functions (Kaltenecker, 1997).

Morphological groups are groups of organisms with the same shape (morphology), general appearance (Belnap *et al.*, 2001b) and similar ecological functionality (Eldridge & Rosentreter, 1999). Morphological groups can be characterized according to appearance (e.g. colour, texture, shape and fruiting structures) and touch (e.g. slimy, brittle, gelatinous, earthy and musty) (Eldridge *et al.*, 2003). In the existing examples Eldridge and Rosentreter (1999) used filament type, colony size, thallus type, thallus height, growth form, thallus continuity, thallus colour and canopy density to develop a recommended framework for morphological group classification. Then, they compared the classified groups with their ecological and management functions. Eldridge and Koen (1998) used colour and growth form for classifying their morphological groups.

3-10-2. Data Collection for BSC Group Classification

There have been some previous studies at the MFC to investigate BSC species composition (Rogers, 1970; Rogers & Lange, 1971; Howarth, 1983). However, these studies did not follow a morphological group classification. Thus, there is little information about the BSC groups at MFC. Identification for this study was made as frequently as possible at the species level (Table

3-8). Reference specimens of taxa identifiable in the field were given a field nomenclature, then collected and identified with the assistance of David Eldridge, then merged for the morphological / functional groups. BSC cover data were collected at 5 × 2 m intervals along 100 m transects (Sections 3-4 & 3-7). Transects were repeated at six different distances from watering points in five different paddocks (total of 30 transects).

Table 3-8. Species and acronyms of BSC components identified in the laboratory (with the assistance of D. Eldridge) and corresponding field identifications in the study area

No.	BSC Species	No.	Field Nomenclature / Reference species	Abbreviation	
	Lichens			Field	Mor./ Fun. Classif.
1	*Cyanobacterium* sp	1	Black cyanobacteria 1 (One observation)	Cya1	Cyas
2	*Cyanobacterium* sp	2	Black cyanobacteria 2	Cya2	Cyas
3	*Chondropsis semiviridis*	3	Leafy 1	Chos	Chos
4	*Cladonia* spp.	4	Leafy 5 (Two observations)	Cla1	Clas
5	*Cladonia foliacea*	5	Leafy 6 (One observation)	Claf	Clas
6	*Collema coccophorum*	6	Black Common Lichen 6	Colc	Colc
7	*Diploschistes ocellatus*	7	White lichen 1	Dipo	Dip
8	*Diploschistes scruposus*	8	White lichen 2	Dips	Dip
9	*Diploschistes thunbergianus*	9	White lichen 3	Dipt	Dip
10	*Endocarpon* spp.	10	Black Common Lichen 1	End1	Ends
11	*Endocarpon pusillum*	11	Black Common Lichen 2	Endp	Ends
12	*Endocarpon rogersii*	12	Black Common Lichen 3	Endr	Ends
13	*Endocarpon simplicatum*	13	Black Common Lichen 4	Ends	Ends
14	*Eremastrella crystallifera (Psora crystallifera)*	14	Black Common Lichen 7	Erec	Erec
15	*Fulgensia subbracteata*	15	White-yellow	Fuls	Fuls
16	*Neofuscelia pulla*	16	Dark Leafy lichen 1	Neop	Neos
17	*Neofuscelia* spp.	17	Dark Leafy lichen 2	Neo1	Neos
18	*Peltula patellata*	18	Black- brown lichen 1	Pele	Pele
19	*Placidium squamulosum*	19	Black Common Lichen 5	Plas	Plas
20	*Psora crystallifera*	20	Black & White lichen	Psoc	Psoc
21	*Psora decipiens*	21	Pinkish or Reddish lichen	Psod	Psod
22	*Xanthoparmelia amphixantha*	22	Leafy 4	Xana	Xana
23	*Xanthoparmelia convoluta*	23	Leafy 2	Xanc	Xanc
24	*Xanthoparmelia molliuscula*	24	Leafy 3	Xanm	Xans
25	*Xanthoparmelia* spp.	25	Leafy 3	Xan1	Xans
	Mosses				
26	*Aloina bifrons*	26	Black Common Mosses	Alob	Alob
27	*Barbula crinita*	27	Tall Mosses	Barc	Bar
28	*Barbula calycina*	27	Tall Mosses	Barca	Bar
29	*Bryum campylothecium*	27	Tall Mosses	Bryc	Bryc
30	*Crossidium geheebii*	26	Black Common Mosses	Crog	Crog
31	*Didymodon torquatus*	27	Tall Mosses	Didt	Didt
32	*Fissidens leptocladus*	26	Black Common Mosses	Fisl	Fiss
33	*Fissidens* spp.	26	Black Common Mosses	Fis2	Fiss

3-10-3. Criteria for Assigning BSC Species to Morphological / Functional Groups

By a review of literature (Eldridge & Koen, 1998; Eldridge & Rosentreter, 1999; Belnap *et al.*, 2001b; Rosentreter *et al.*, 2001; Bechtel *et al.*, 2002; Rosentreter & Eldridge, 2002) two criteria: colour and trampling tolerance (sensitivity to disturbance) were used in addition to the morphological criteria used by Eldridge and Rosentreter (1999) for BSC group classification. The colour criterion has already been used to some degree by Eldridge and Rosentreter (1999) for morphological group classification, and I used it for BSC classification because the purpose was for later use in remote sensing, therefore linking is important. The framework of Eldridge and Rosentreter (1999) formed the basis of this study, so morphology was the base, then defined criteria (colour and sensitivity to disturbance) were considered for each collected species and compared with the proposed groups. If, by considering defined criteria, a given species could be placed in one of the groups of Eldridge and Rosentreter (1999), the species were kept as the same group but if there were different characteristics identified (colour and habitat sensitivity) then they were classified as a new group. For example, crusty lichens have specific characteristics as a separate group from this study perspective similar to that of Eldridge and Rosentreter (1999), thus they are classified as a Crusty group (Appendix B-5a). All, scaly lichens (*Psora* spp.) with very high colour and trampling-tolerance are classified as Scaly (Appendix B-5b) as per Eldridge and Rosentreter (1999). Leafy lichens (Appendices B-2b & B3a-b) have high variation in morphology and colour, but have almost the same ecological functionality. In this study all leafy species were classified as one group, except for black leafy lichens (*Neofuscelia* spp.), which were classified in the Black Lichens, because of their possible importance from a remote sensing perspective.

3-10-3-1. Colour

Soil crusts exhibit a wide range of colour, which is generally attributed to high densities of chlorophyll-bearing algae (Belnap *et al.*, 2001b). Some soil crusts with symbionts of various cyanobacteria appear blue-green and some others with a concentration of diatoms and yellow algae can exhibit a yellow colour. There is some evidence for relationships between some soil crusts with specific colour and their ecological functionality (Eldridge & Koen, 1998; Eldridge & Rosentreter, 1999) and colour is obviously useful for identifying BSC groups in the field. For example, Eldridge and Koen (1998) used colour to name each group, and in the (Eldridge & Rosentreter, 1999) framework one of the criteria for assigning each species to a group was colour.

The effect of soil crust colour on remote sensing signals is important (Ager & Milton, 1987; Lodhi & Rundquist, 2001; Bechtel *et al.*, 2002). For example, spectral variation in the region of

400-2500 nm of soil crusts is solely due to colour (Ager & Milton, 1987). Bechtel *et al.* (2002) to avoid these colour difference effects, selected soil crust samples within the same colour range to study differences in spectral properties of arctic foliose and crustose lichens. The concentration of pigments such as chlorophyll varies in different growth stages of various soil crusts. The presence of different pigments in the soil crusts and the effects of growth-stage on colour change mean that it is necessary to include colour as an attribute in a soil crust classification, if this classification is to be used in remote sensing studies.

There was a very large colour variation in the species collected, with considerable colour variation even in the same species. *Psora* spp. had the highest colour variation including white, red, pink, green, grey and black in mixed patterns. By contrast, species such as *Chondropsis semiviridis* and *Xanthoparmelia* spp. had the lowest colour variation, both being usually light-green to yellow-green. Overall, the main colours of collected specimens can generally be considered as black, grey, brown, white, red, yellow and green with a variety of sub-colours such as dark-green, dark-brown, etc.

3-10-3-2. Sensitivity to Disturbance (Trampling Tolerance)

Although, initially soil-based crusts were defined as the aim of this study, stone-based and vegetation-based crusts were also considered. There was a very low cover (0.27%) of stone-based crusts on the study sites. Vegetation-based lichens also had very low cover (<0.01%) in 30 transects, mostly because the stratification avoided woodland communities. Soil-based crusts are by far the dominant group, so this study dealt with soil-based crusts only.

Habitat-class was determined by whether particular BSC are sensitive to disturbance (trampling) or are trampling tolerant. Trampling by humans, animals and vehicles is known to reduce the cover and density of crusts and ultimately can destroy their component microfloras (Rogers & Lange, 1971; Eldridge & Koen, 1998; Rosentreter & Eldridge, 2002). The sensitivity of the crusts to external forces is important from both ecological and management perspectives. According to Eldridge and Koen (1998), the yellow foliose group comprising lichens of the genera *Heterodea* spp., *Xanthoparmelia* spp. and *Chondropsis semiviridis* were consistently correlated with stable site and soil situations. This is probably due to the differences in their morphologies as foliose or fruticose forms, which are obviously more susceptible to trampling than crustose and squamulose forms (Eldridge & Rosentreter, 1999). Trampling-tolerant BSC live in different parts of a paddock even around watering points.

Uncommon or rare species such as *Xanthoparmelia* sp., *Bryum* spp., *Cyanobacterium* sp. and *Neofuscelia* spp. mostly grow near and under vascular plant shadow. Thus, these types of species have specific habitat requirements. They are also highly sensitive to disturbance so

cannot be grouped with habitat-tolerant lichens and mosses. In the group classification, these types of components with specific habitat requirements were defined as separate groups.

3-10-4. Methods of Classifying the Morphological / Functional Groups

Initially, all collected species were placed in the morphological groups used by Eldridge and Rosentreter (1999) to standardize and link this study to that framework. As a second step colour, and grazing-tolerance or sensitivity were considered and used to modify the classification if necessary. There were some exceptions in following that framework: for example, *Neofuscelia* spp. with black colour in comparison with other leafy lichens and rare distribution (less than 0.005%), were merged with black common lichens. Most of the black BSC such as *Endocarpon* spp. or *Placidium* spp. are not gel-like lichens such as *Collema* spp., but there is a possibility that they could have similar spectral characteristics (See Ch.5). Thus, they were merged with each other and the name of Black Common Lichens (Appendix B-2a) was chosen for that broad group of BSC.

Other species were mostly classified into the same groups as Eldridge and Rosentreter's (1999) framework with the exception of the mosses group where two sub-groups were defined: Black Common Mosses and Tall Mosses. Tall and short mosses have been defined in the US literature (Belnap *et al.*, 2001b). They defined "short mosses" as less than 10 mm and "tall mosses" as more than 10 mm. These height categories cannot work for this study. The heights of all mosses for MFC are less than 10 mm, thus following Catcheside (1980) less than 3 mm was considered as Black Common Mosses and more than 3 mm as Tall Mosses. This classification was mainly used to define a group of mosses with specific habitat requirements (very high trampling-sensitivity) (Tall Mosses) versus mosses with ubiquitous habitat (Black Common Mosses).

3-10-5. Some Considerations in Assigning Species to Morphological / Functional Groups

This study, by considering existing literature (Eldridge & Koen, 1998; Eldridge & Rosentreter, 1999; Rosentreter & Eldridge, 2002), focused on the macroscopic BSC to classify morphological / functional groups. Although algae and bacteria are a part of most BSC communities (Eldridge & Rosentreter, 1999; Belnap & Lange, 2001) they are not included in this classification because it is almost impossible to determine their presence in a field setting. In addition, liverworts (sub-group of bryophytes according to Eldridge (2001) are one of the main BSC components on the rangelands of Australia. However no liverworts were collected along 30 transects so they were not included in this classification. This is probably because the stratification used avoided the selection of sample sites in low-lying areas, which are more likely to remain damp after rain and

provide suitable habitat for liverworts. Moreover, from the shrubby / leafy lichen group only leafy crusts were found in the study area and included in this classification.

3-10-6. Morphological / Functional Groups of BSC in the Study Sites

Table 3-9 shows the final classification of BSC of the study area into six functional-morphological groups, following Eldridge and Rosentreter's (1999) classification, but modified for colour and trampling-sensitivity. The Black Common Lichens (Appendix B-2a), Black Common Mosses (Appendix B-2a) and Scaly Lichens (Appendix B-5b) are habitat-tolerant. Leafy Lichens (Appendices B-2b & B-3a-b), Crusty Lichens (Appendix B-5a) and Tall Mosses (Appendix B-6a-b) are either specific habitat or they are sensitive to disturbance.

Table 3-9. Morphological / functional groups and the criteria used to classify them [based on Eldridge and Rosentreter (1999) morphological classification]

Species (Field collected taxa)	**Criteria**		**Final allocation of morphological / functional group**
	Colour	**Habitat-tolerance or sensitivity to trampling**	
Cyanobacterum spp., *Collema* spp., *Endocarpon* sp., *Endocarpon pusillum, Endocarpon rogersii, Endocarpon simplicatum, Neofuscelia pulla, Neofuscelia* sp., *Placidium squamulosum*	Black, dark-grey, dark-brown,	habitat tolerance (ubiquitous) or macro habitat and low sensitivity to trampling	Black Common Lichens
Diploschistes ocellatus, Diploschistes scruposus, Diploschistes thunbergianus	White-greyish	habitat tolerance (ubiquitous) or macro habitat and moderate sensitivity to trampling	Crusty Lichens
Fulgensia bracteate, Fulgensia subbracteata, Peltula patellata, Psora crystallifera , Psora decipiens	Black & white, reddish, yellow, green-grey (with high variation)	habitat tolerance (ubiquitous) or macro habitat and moderate sensitivity to trampling	Scaly Lichens
Chondropsis semiviridis, Cladonia sp., *Cladonia foliacea, Xanthoparmelia amphixantha, Xanthoparmelia convoluta, Xanthoparmelia molliuscula, Xanthoparmelia* sp.	Yellow-green, light green (with low variation)	habitat tolerance (ubiquitous) to specific or macro to micro habitat and high sensitivity to trampling	Leafy Lichens
Aloina bifrons, Crossidium geheebii, Fissidens spp.	Black, dark-grey, dark-brown, dark green, green-brown	habitat tolerance (ubiquitous) or macro habitat and low sensitivity to trampling	Black Common Mosses
Barbula crinita, Barbula calycina, Bryum campylotheciium, Didymodon torquatus,	Dark-green to dark-brown,	Specific or micro habitat and moderate sensitivity to trampling	Tall Mosses

The relative cover of BSC groups over the study sites is presented in Figure 3-20. The Black Common Lichens with 62.05% of total BSC cover is the most prevalent BSC group. The

second most important group is the Black Common Mosses with 20.18% of the total BSC cover. The third major group is the Scaly Lichens with 12.3% of the total BSC cover. Leafy Lichens with 2.84% are in fourth place and show a high variation in response to grazing pressure close to, and away from watering points (Figure 3-20 and Appendix B-1). Leafy Lichens, in spite of their low overall cover, can be present at very high density under ungrazed conditions such as outside of the Railway paddock, where, at small scales (less than 1 m), their percentage cover is nearly 70% to 100% (Appendix B-2b). Crusty Lichens with nearly 1.90% of total BSC cover are in fifth place and finally Tall Mosses with 0.45% of the total BSC cover are in sixth place. Other lichens, mainly groups of lichens distributed on stone and vegetation-based habitat, at 0.28%, are the lowest BSC cover in the study sites. The total percentage cover of all lichen groups is 79%, thus the BSC at MFC is lichen-dominated. Full details of morphological / functional group percentage cover in each paddock are presented in Appendix B-1.

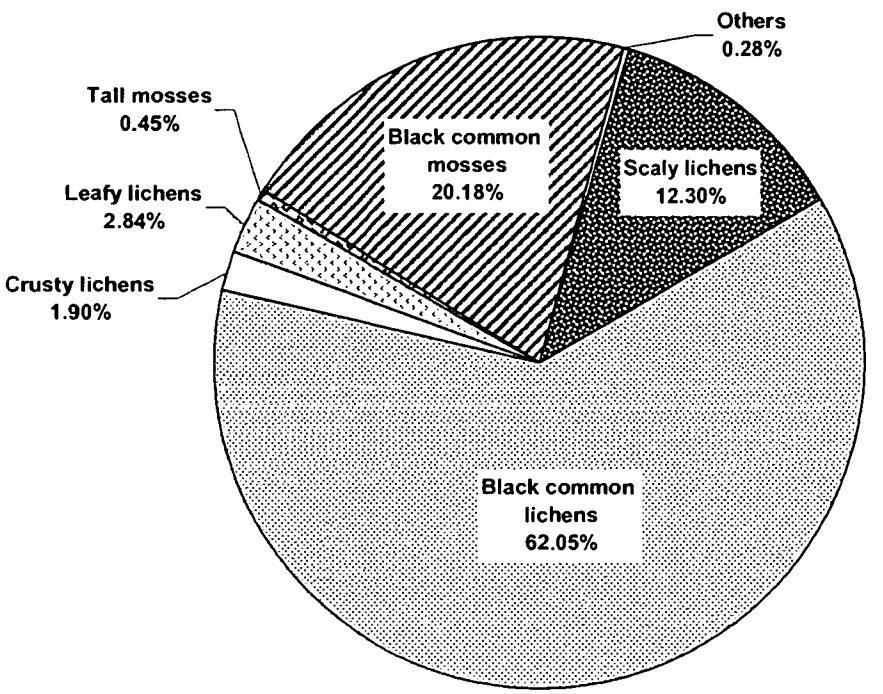

Figure 3-20. Total cover of the six main morphological / functional groups of BSC over the study area (five paddocks). The total cover of lichens is 79% and of mosses is 21%.

CHAPTER 4

4. DETERMINATION OF LAND COVER COMPONENTS INCLUDING BSC BY GROUND-BASED METHODS

This chapter
Little evidence exists for BSC cover analysis within the piosphere framework. This chapter aims to analyze BSC cover variance within piosphere gradients to ascertain if BSC are a reliable indicator for rangeland condition assessment. The validation of a BSC cover gradient in piospheres was important for this study, because current remotely-sensed methods of rangeland condition assessment do not take BSC cover into account, which could create ambiguity in their results. Therefore, this chapter analyzes the relationship of land covers including BSC with piosphere gradients using ground-based methods. If BSC cover is a reliable indicator of grazing intensity, then the study will move to the next step of incorporating BSC in monitoring by remotely-sensed methods.

4-1. Introduction

As reviewed in Chapters 1 and 2, there is no agreement that BSC cover alone is a good indicator of land degradation and some authors have concluded that BSC cover is a weak indicator (Eldridge & Koen, 1998; Rosentreter & Eldridge, 2002). Although these studies have employed some pre-assessment methods such as classification of BSC into morphological groups, or reduction in the effect of seasonality patterns by wetting the BSC prior to sampling, some other methods such as site stratification and sampling method selection have been less considered. This chapter examines the importance of BSC cover as an indicator of rangeland condition following the use of site stratification and line-intercept data collection. If BSC cover has a reliable relationship with piosphere gradients, then it is valuable to include BSC in remote sensing methods of rangeland condition assessment.

4-2. Canopy Cover and Ground-Based Methods

As described in Chapter 2 vascular plant cover assessment by ground-based methods has been well established in literature (Canfield, 1944; Kinsinger *et al.*, 1960; Brun & Box, 1963; Hanley, 1978; Arzani & King, 1994; Pyke *et al.*, 2002), however, BSC cover investigations have been less considered (Eldridge & Koen, 1998).

4-3. Aim of Chapter

The main objective of this chapter was to examine the significance of cover variation of BSC at different distances from watering points, making the assumption that trampling effects on BSC are proportional to the distance from watering points, If BSC cover is a good indicator of trampling, then employing remotely-sensed methods to detect them would be a suitable tool for rangeland condition assessment.

4-4. Methods

4-4-1. Data Collection

A 100 m line-intercept (3-4) was used for ground data collection at six distances from watering points in five replicate paddocks. Sites were stratified only to include shrubland and shrub-woodland physiognomic communities (3-5). Data were collected and classified for different components such as vascular plants, BSC, bare soil and litter. Stones larger than 7 to 9 cm were initially defined for data collection as a separate group, but on the sampling sites the stone cover on the soil surface was very low or smaller than the 7 to 9 cm, thus it was equated to bare ground. All land covers were collected because, in remotely-sensed methods where pixel-based data are obtained, image interpretation requires data for all land cover components.

4-4-2. Gradient Identification

Ecologists are generally interested in understanding patterns in the distribution and abundance of organisms and the ecological or environmental factors that control those patterns (McGarigal *et al.*, 2000). One way of doing this is by identifying patterns in the distribution of organisms and secondly identifying ecological or environmental factors that help to explain those patterns. Alternatively, relationships can be identified by first detecting patterns in the environment and then determining the response of organisms to those patterns (McGarigal *et al.*, 2000). This thesis examined the BSC cover variance (patterns) along the piosphere gradient (distance from watering- points), which was assumed to be proportional to trampling pressure on BSC. For gradient identification, cover of all components was plotted against distance from watering-point allowing comparison among different land covers. In the second stage, BSC cover variance along piosphere gradients of the six morphological / functional groups identified in Section 3-10 were statistically analyzed. It should be emphasized that the analysis, as identifying ecological or environmental factors that help to explain those patterns, was not covered in this thesis.

4-4-2-1. Gradient Identification with and without BSC

In the second step, before statistical analyses of different BSC components in response to trampling pressure, a profile plot of general gradient patterns was derived from photosynthetic components with and without BSC. It was conducted to investigate the share of BSC in the piosphere patterns to determine the importance of their cover in the overall gradient patterns. Gradient patterns of each model were derived from collected data according to Table 4-1.

Table 4-1. Piosphere gradient models and cover value calculation for land covers

Model	Cover calculation with and without BSC
Vascular plants (annuals + perennials) without BSC	(*Acacia* spp. × % cover) + (*Atriplex* spp. × % cover) + ... + (annual grasses × % cover) + (annual forbs × % cover) without BSC
Vascular plants (annuals + perennials) with BSC	(*Acacia* spp. × % cover) + (*Atriplex* spp. × % cover) + ... + (annual grasses × % cover) + (annual forbs × % cover) + ...+ (scaly lichens × % cover) + (crusty lichens × % cover) + ...

4-4-3. Data Analysis

The significance of any relationships between cover of BSC components and distances from water was tested using analysis of variance and general mixed models using S-Plus v6.2 for Windows (Insightful Corporation, 2003), the SAMM (Spatial Analysis Mixed Models) add-in library (Butler *et al.*, 2004) and Genstat (Payne *et al.*, 2000). In the analyses, distance from water was assumed as the independent variable and the cover of the various BSC components as dependent variables in a two-way table indexed by five paddocks and six distances.

Initially mixed models were used to determine whether the model for the variance and correlation for the data should incorporate: a) equal or unequal plot variances for the different distances and b) correlations between the observations at different distances that decay as a power of the difference in the distance. None of the decaying correlation models fitted and so approach b) was discarded.

Having decided on the model for the variances and correlations, the investigation of the relationship between mean cover and distance was conducted and the analyses based on general mixed models if unequal variances were required, and on the analysis of variance if equal variances were considered appropriate. There is extensive literature for environmental gradient analysis, or response of a given organism to environmental variables such as temperature and rainfall (Austin & Cunningham, 1981; ter Braak, 1987; ter Braak & Prentice, 1988; Austin & Gaywood, 1994; Austin *et al.*, 1994); however for piosphere analyses, or the effects of an artificial variable such as grazing pressure, literature is poor. The recommended models for grazing pressure analysis in the framework of the piosphere can be divided into those which are: a) linear b) asymptotic (sigmoidal) (Graetz & Ludwig, 1978). The sigmoidal model was not

suitable for this study because the collected data did not display a lower asymptote. Thus linear and exponential models were tested for the collected data. In the first step, if a linear trend (model) proved to be inadequate then an exponential curve was investigated for describing the trend of data. The general equation of the exponential (or asymptotic) curve was:

$$Y_i = \alpha + \beta \times \rho^{\text{Distance}_i} \qquad \text{equation 4-1}$$

where α is the asymptote (Payne *et al.*, 2000). In all cases where an exponential curve needed to be fitted, the model for the variances involved only equal variances for the distances and so the investigation of trend of data could be based on the analysis of variance.

4-5. Results

4-5-1. General Cover Patterns of Land Covers

For identifying, describing and comparing BSC patterns in different paddocks at different distances from water, profile plots of collected data for six categories of land covers (Figure 4-1 & Appendix C-1) were developed to give a graphic description of the data for total BSC and other covers.

As would be expected bare ground cover decreases as the cover of other land covers increases (Figure 4-1).

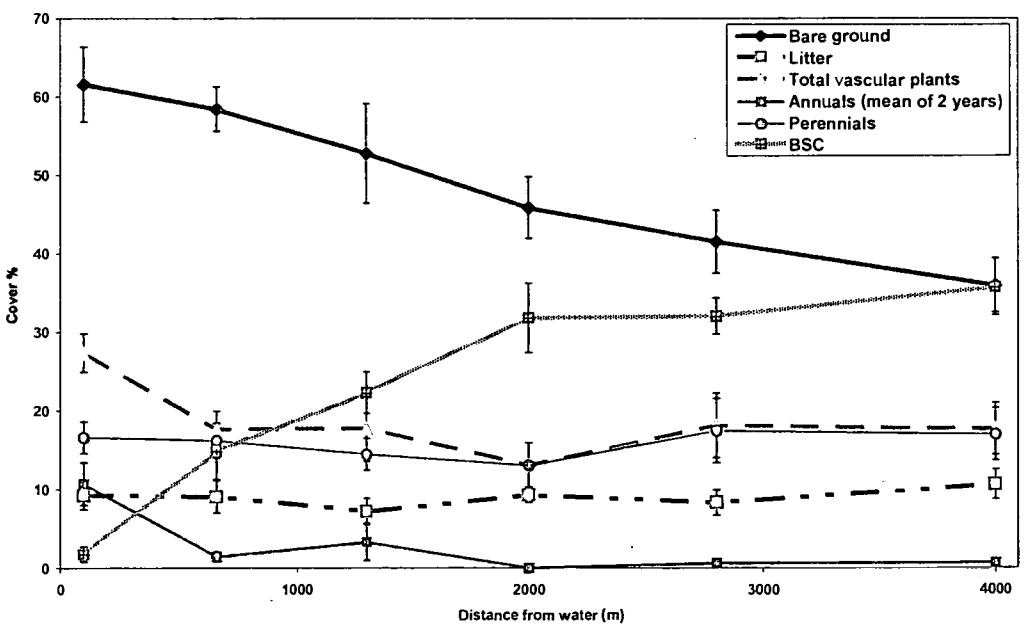

Figure 4-1. Cover component patterns, mean cover values for each component ± standard error (vertical bars) along a piosphere in five paddocks at MFC

Data for annuals were collected over two consecutive years (March 2003 to July 2005) (Appendix E-6), the first with medium rainfall and the second dry in comparison with annual

mean rainfall of the study area. By monthly observations during this study, there was no evidence of summer annuals in the study area. Thus, the annual percentage cover (Figure 4-1 & Appendix C-1) is related to the winter annuals only, expressed as a mean of the two years. There is an increase in cover of winter annual near watering points (Figure 4-1).

Perennials have commonly been used as a response indicator for degradation in both ground-based and remotely-sensed methods. However, as can be seen from Figure 4-1 and Appendix C-1, there is no discernable change in the total percentage cover of perennials along a piosphere gradient. As described in Chapter 3, another characteristic is the location of several of the watering points in woodland communities, possibly to provide shade for sheep which could bias the response of BSC, because of the negative relationship between BSC and these communities. In Billabong and Railway paddocks, there were opportunities along the main transects to select sampling locations to avoid woodland communities, but in the other paddocks it was impossible.

The results of litter data (Figure 4-1 & Appendix C-1) show that there is no distinct relationship with distance from water. The amount of litter cover in the study area is 7.20 (± 1.68) to 10.65 (± 1.91) % cover.

As can be seen from Figure 4-1, Total BSC have a visible positive gradient with increasing distance from water.

4-5-2. Effects of BSC Cover on Grazing Gradient Patterns

Deriving BSC cover pattern without taking into account their patterns in the context of general photosynthetic components has low value from the ground-based and remote sensing perspectives. Thus, integrated results of photosynthetic components by considering each major element including BSC, perennials and annuals were considered. An integrated model in the context of piosphere is presented in Figure 4-2. Total vascular plants gradient versus total photosynthetic components gradient are significantly different with and without BSC. There is an "inverse gradient" (2-7) without BSC, whereas, there is a "normal gradient" (2-7) with BSC. The second major point is the cover value differences: for example, at 100 m and 4000 m the percentage cover values without BSC are about 27.37 (± 2.44) and 17.69 (± 3.31), respectively. On the other hand, with BSC, percentage cover is between 29.13 (± 5.72) and 53.41 (± 5.64), respectively. That is, there is less than a 2% difference in the cover value (percentage cover) because of the BSC cover at 100 m and more than a 24% difference at 4000 m. This is important from a soil stability and cover value perspectives in remotely-sensed methods, particularly if derived cover is applied for a secondary analysis such as erosion or biomass estimation.

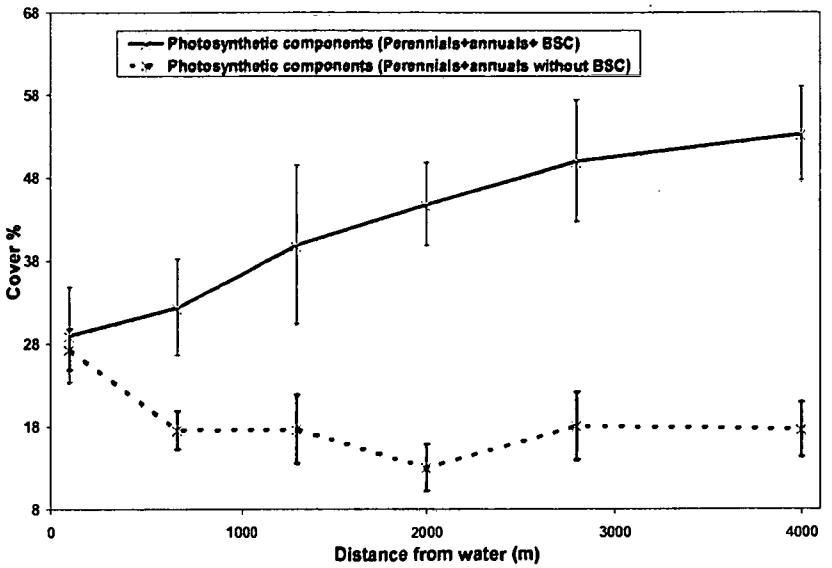

Figure 4-2. Profile plots of photosynthetic components distribution and mean cover value ± standard error at different distances in five paddocks at MFC

4-5-3. Results of Statistical Analyses of Total BSC Cover

BSC cover data were analyzed to determine if there was a significant change in BSC cover at different distances from water. A likelihood ratio test comparing the analysis of variance model with the heterogeneous variance model was not significant ($p = 0.200$) and so it was concluded that there was no evidence for employing the heterogeneous variances model. As a result, an analysis of variance in which a straight line was fitted to the distance means was performed ($p<0.001$). Results of the statistical output are given in Table 4-2 and Appendix C-2. From this result it was concluded that there were significant deviations from the linear trend ($p<0.031$) and an exponential curve was fitted to the trend (Figure 4-3). The equation of the fitted curve is presented in Table 4-2.

Table 4-2. P-values of fitted curve for total BSC cover (summarized from Appendix C-2). The extended analysis of variance in Appendix C-2 shows that there were no significant deviations from the exponential curve ($p = 0.984$), thus the exponential curve was significant ($p < 0.004$)

Model	Linear / Exponential	Deviation
Linear	0.000 (< 0.001)	0.031
Exponential	0.004	0.984
Equation of fitted curve	Total BSC Cover = $36.99 - 38.31 \times 0.999182^{\text{Distance}}$	

Figure 4-3 shows that there is a significant increase in BSC cover with increasing distance from water in five paddocks, even taking into account the variation from paddock to paddock. Following the pilot study results, which were conducted to establish a framework for data collection, it was observed that there was a relationship between soil, topographical variation and vegetation type with BSC distribution (Ch.3). Stratification of sampling was

carried out (3-5) to remove these factors as possible sources of variation or noise in the BSC data, but obviously, they could not be completely eliminated.

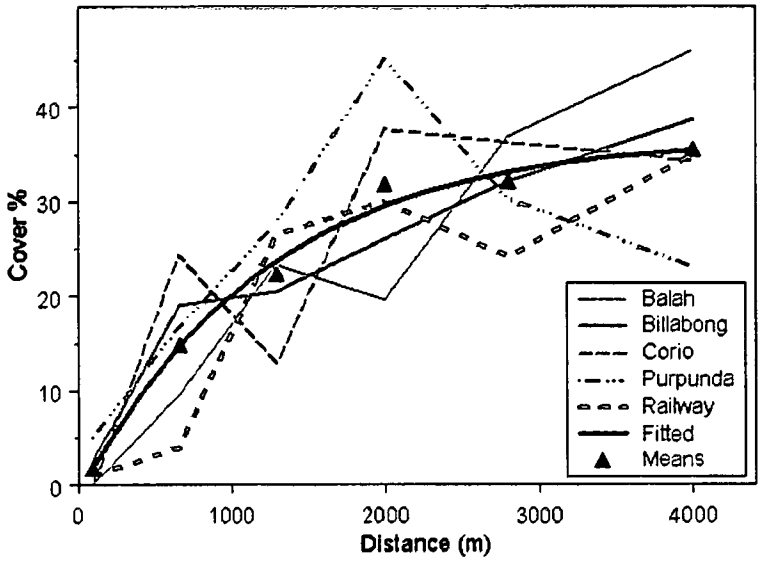

Figure 4-3. Profiles, means and fitted exponential curve ($p<0.004$) for total BSC cover along a piosphere gradient in five paddocks at MFC

Overall, the predicted maximum amount of BSC cover over the communities sampled at five paddocks is, from the asymptote of the fitted curve, 36.99%. On the other hand the predicted cover at 100 m, using the fitted equation, is 1.69% so that BSC cover in this zone is only 21.89% of the maximum observed on less degraded sites. The percentage cover of BSC at the sites with less trampling pressure was between 30 to 45% in 73% of the sites at 2000 m to 4000 m. The cover in 27% of the sites was between 19 to 30%.

4-5-4. Results of Statistical Analyses of Total Lichen Cover

The same procedure as for total BSC cover was performed for lichen cover analyses. For this analysis heterogeneous variance was insignificant ($p = 0.183$), and so it was concluded there was no evidence for employing the heterogeneous variances model. Consequently, an analysis of variance in which a straight line was fitted to the distance means was performed ($p>0.001$) (Appendix C-3). From this it was concluded that there are significant deviations from the linear trend ($p < 0.016$). Therefore an exponential model was fitted to the trend (Table 4-3 & Figure 4-4). The extended analysis of variance in Appendix C-3 indicates that there are no significant deviations from the exponential curve ($p = 0.999$) and that the exponential curve is significant ($p= 0.003$). Summarized p-values and fitted curve equation are presented in Table 4-3.

The pattern and trend of lichen distribution (Figure 4-4) is significantly positive with distance from water and is strongly similar to the total BSC distribution.

Table 4-3. P-values of fitted curve for total lichen cover (summarized from Appendix C-3)

Model	Linear / Exponential	Deviation
Linear	0.000 (< 0.001)	0.016
Exponential	0.003	0.999
Equation of fitted curve	Total lichen cover = $28.181 - 29.474 \times 0.9990602^{\text{Distance}}$	

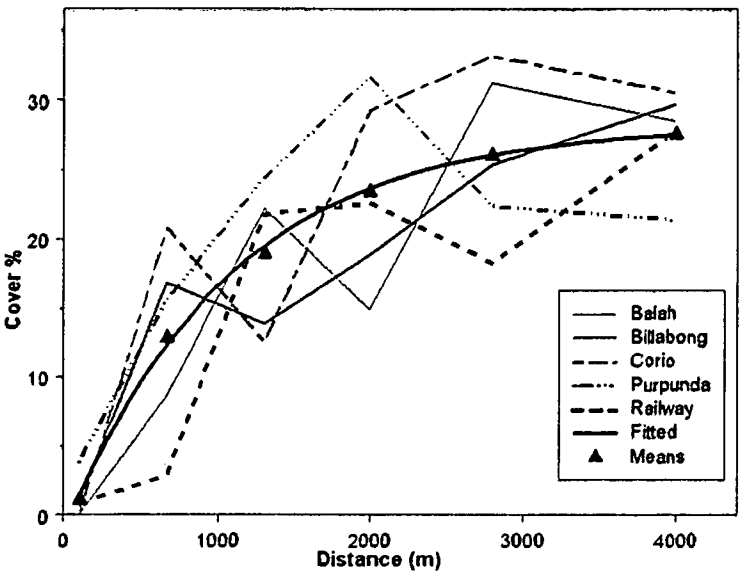

Figure 4-4. Profiles, means and fitted exponential curve ($p<0.003$) for total lichen cover in five paddocks at MFC

4-5-5. Results of Statistical Analysis of Total Moss Cover

A likelihood ratio test comparing the analysis of variance model with the heterogeneous variances model was significant ($p < 0.001$). Thus, a model involving heterogeneous variances was appropriate and the estimated variances are given in Appendix C-4. To determine which curve was required to describe the trend with distance required the fitting of general mixed models and the use of Wald tests (Appendix C-5). From this, it was concluded that there were no significant deviations from a linear trend ($p = 0.077$) which was significant ($p < 0.001$). The fitted equation is presented in Table 4-4.

Table 4-4. P-values of fitted line for total moss cover (summarized from Appendices C-4 & C-5)

Model	Linear	Deviation
Linear	0.000 (< 0.001)	0.077
Equation of fitted line	Total Moss Cover = 0.4094 + 0.002046 Distance	

There is a discernable piosphere gradient for total moss cover (Figure 4-5), but it varies from those of the total BSC and lichen cover in that the relationship is linear rather than asymptotic, so that an asymptotic model may not fit the data.

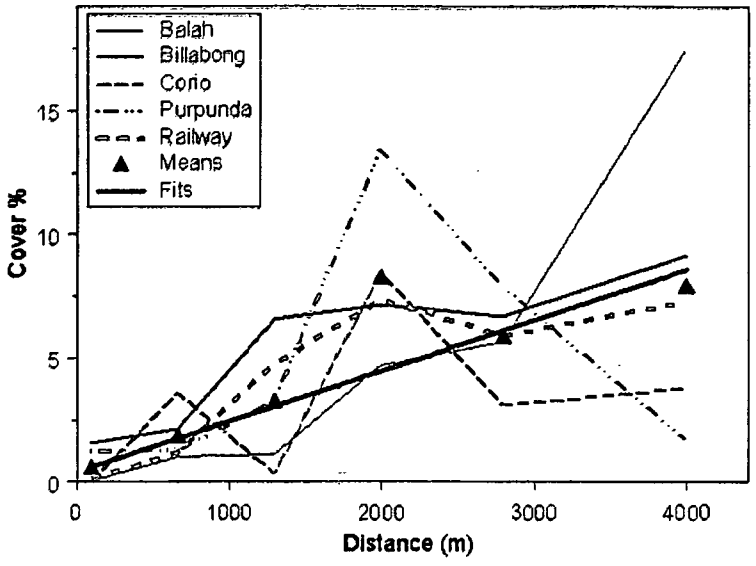

Figure 4-5. Profiles, means and fitted linear model ($p<0.001$) for total moss cover in five paddocks at MFC

4-5-6. Results of Statistical Analysis of BSC Morphological/ Functional Groups

Before statistical analysis of BSC groups, it should be noted that the distribution of some lichen and moss groups such as Crusty and Leafy Lichens, and Tall Mosses is very low in comparison with the other land covers and BSC groups. A question can be raised about how the sampling method could determine the cover of these components with their small distribution. Therefore, there is the possibility of the effects of techniques used as noise in the determined covers as miss estimation, particularly for the Tall Mosses, which is a fraction of 1%. Overall, it should be clarified, on the defined sampling sites all land covers were collected with the same procedures as in all ground-based and ground-truthing studies. Therefore, if there is a noise, it will be common with all components, and not just with the small groups. Presented cover values for different land covers are the results of observed and collected data on the defined sampling sites.

4-5-6-1. Black Common Lichen Cover

An analysis of variance model with the heterogeneous variances model using a likelihood ratio test was not significant ($p = 0.107$), thus, it was concluded that there was no evidence to employ the heterogeneous variances model. Therefore, an analysis of variance in which an exponential model was fitted ($p<0.001$) to the distance means was performed (Figure 4-6). Statistical output of this analysis is given in Appendix C-6. Thus, it was concluded that there are significant deviations from the linear trend ($p < 0.016$) (Table 4-5). The equation of the fitted exponential model and p-values are given in Table 4-5.

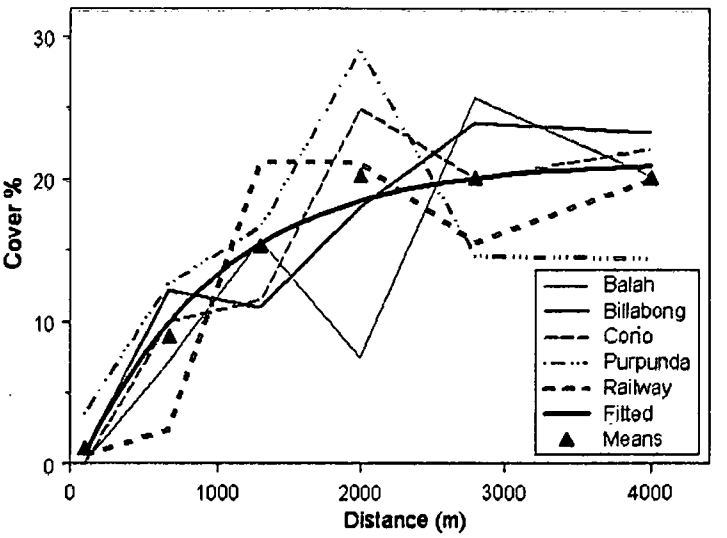

Figure 4-6. Profiles, means and fitted exponential curve ($p<0.001$) for total Black Common Lichen cover in five paddocks at MFC

Table 4-5. P-values of fitted curve for total Black Common Lichen cover (summarized from Appendix C-6). The extended analysis of variance in Appendix C-6 indicates that there are no significant deviations from the exponential curve ($p < 0.921$) and that the exponential trend is significant ($p < 0.001$)

Model	Linear / Exponential	Deviation
Linear	0.000 (< 0.001)	0.016
Exponential	0.000 (<0.001)	0.920
Equation of fitted curve	Black Common Lichen = $21.23 - 22.87 \times 0.998939^{Distance}$	

Black Common Lichens (BCL) are the dominant BSC at MFC (3-10). As expected the general cover pattern of this group is similar to that of total BSC (Figures 4-1 & 4-3) and total lichen (Figure 4-4) cover. From these results, although there are some fluctuations between the paddocks, it can be concluded that one of the main influence BSC groups on the piosphere pattern at MFC is Black Common Lichens.

4-5-6-2. Scaly Lichens

A likelihood ratio test comparing the analysis of variance model with the heterogeneous variance model was significant ($p < 0.001$) and so a model involving heterogeneous variance was required. The estimated variances are given in Appendix C-7. To determine whether a straight line adequately describes the trend with distance required the fitting of general mixed models and the use of Wald tests (Appendix C-8). From this it was concluded that there were significant deviations from a linear trend ($p = 0.026$). However, there is no obvious alternative curve that could be used to provide a better description of the trend because the deviations seem to be distributed randomly around the fitted straight line (Figure 4-7). Therefore the fitted equation for the linear trend, although inadequate in describing the trend, is given in Table 4-6.

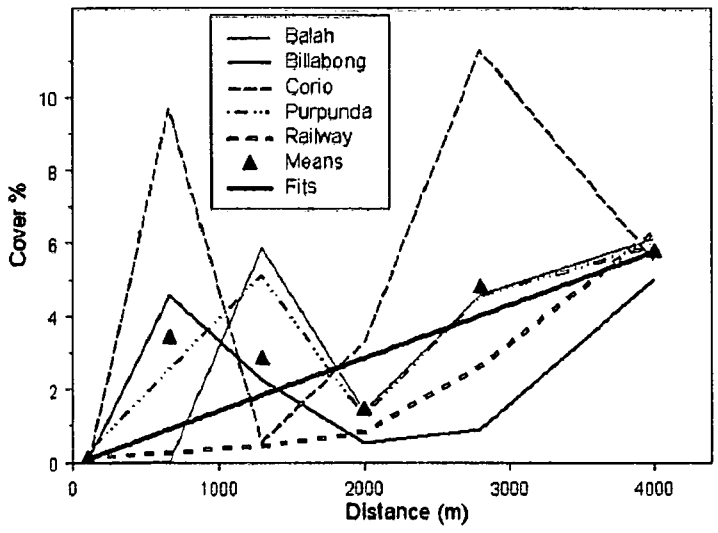

Figure 4-7. Profiles, means and fitted linear trend for Scaly Lichens, however there was a significant deviation from the linear trend (p=0.026) in five paddocks at MFC

Scaly Lichens, after Black Common Lichens and Black Common Mosses, are the most common BSC group at MFC (3-10). As can be seen from Figure 4-7, the fluctuation in cover of this group between sites and paddocks is very large in comparison with other groups.

Table 4-6. P-values of the fitted line for total Scaly Lichen cover (summarized from Appendices C-7 & C-8)

Model	Linear	Deviation
Linear	0.000 (< 0.001)	0.026
Equation of fitted line	Total Scaly Lichens = –0.04524391 + 0.001452595 Distance	

4-5-6-3. Crusty Lichens

Statistical analysis was performed using a likelihood ratio test comparing the analysis of variance model with the heterogeneous variances model, which was significant ($p < 0.001$). As a result, it was concluded that a model involving heterogeneous variances was required. The estimated variances details are presented in Appendix C-9. To determine whether a straight line adequately described the trend with distance of a general mixed model was fitted and tested using the Wald statistic (Appendix C-10). From this, it was concluded that there are no significant deviations from a linear trend ($p = 0.606$), which was significant ($p < 0.001$). The fitted equation and p-values are given in Table 4-7. Profiles, means and fitted linear trend of Crusty Lichens are presented in Figure 4-8.

Table 4-7. P-values of fitted line for total Crusty Lichen cover (summarized from Appendices C-9 & C-10)

Model	Linear	Deviation
Linear	0.000 (< 0.001)	0.606
Equation of fitted line	Total Crusty Lichens = 0.02015 + 0.00026 Distance	

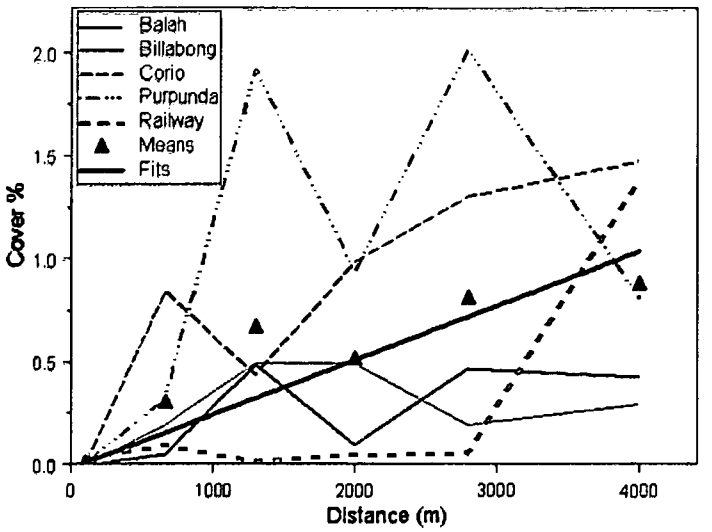

Figure 4-8. Profiles, means and fitted linear trend ($p<0.001$) for total Crusty Lichen cover in five paddocks at MFC

4-5-6-4. Leafy Lichens

For Leafy Lichens a likelihood ratio test comparing the analysis of variance model with the heterogeneous variances model was significant ($p < 0.001$), thus a model involving heterogeneous variances was required (Appendix C-11). To decide which curve was required to describe the trend with distance required the use of Wald tests (Appendix C-12). From this, it was concluded that there were no significant deviations from a linear trend ($p = 0.762$), which was significant ($p = 0.003$). The profiles, means, fitted line and equation for Leafy Lichens and p-values are given in Figure 4-9 and Table 4-8.

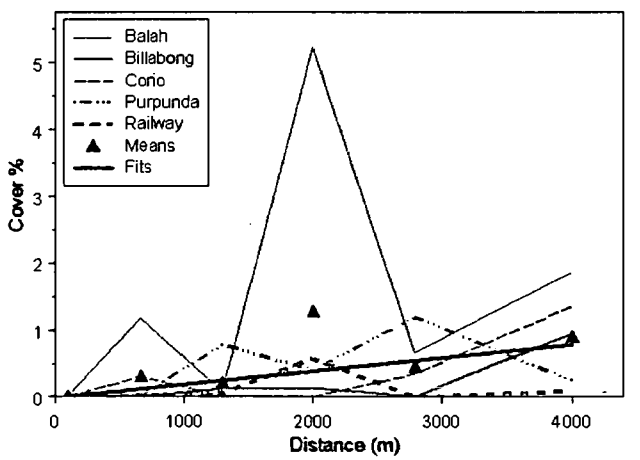

Figure 4-9. Profiles, means and fitted linear model ($p=0.003$) for total Leafy Lichens cover in five paddocks at MFC

Table 4-8. P-values of fitted line for total Leafy Lichens cover (summarized from Appendices C-11 & C-12)

Model	Linear	Deviation
Linear	0.003	0.762
Equation of fitted line	Total Leafy Lichen = 0.02007 + 0.0002007 Distance	

4-5-6-5. Black Common Mosses

The second major BSC group at MFC (3-10) is Black Common Mosses (Figure 4-10). The cover pattern is similar to the total moss pattern because of the low percentage cover of the Tall Mosses.

A likelihood ratio test was performed to compare the analysis of variance model with the heterogeneous variances model. Results showed that there was significant ($p < 0.01$) variation between the distances, so a model relating heterogeneous variances was required. The details of estimated variances are presented in Appendix C-13. To determine whether a straight line adequately described the trend with distance required the fitting of a general mixed model and the use of Wald tests. The results of the Wald test are given in Appendix C-14. From this, it was concluded that there were no significant deviations from a linear trend ($p = 0.149$) which was significant ($p < 0.001$); the fitted equation is presented in Table 4-9.

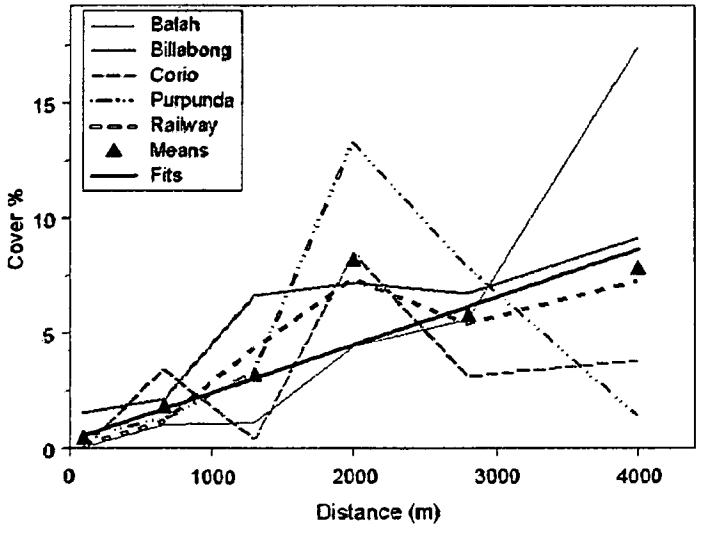

Figure 4-10. Total Black Common Mosses cover profile, mean and fitted linear model ($p<0.001$) at different distances from water in five paddocks at MFC

Table 4-9. P-values of fitted line for total Black Common Moss cover (summarized from Appendix C-13 & C-14)

Model	Linear	Deviation
Linear	0.000 (< 0.001)	0.149
Equation of fitted line	Total Black Common Moss = 0.3423756 + 0.002074453 Distance	

4-5-6-6. Tall Mosses

A likelihood ratio test comparing the analysis of variance model with the heterogeneous variances model was significant ($p< 0.01$), so a model involving heterogeneous variances was required (Appendix C-15). To determine which curve was required to describe the trend with distance required fitting of a general mixed model and the use of the Wald tests. The results of the Wald test are given in Appendix C-16. From this, it was concluded that there are no significant deviations from a linear trend ($p = 0.858$) and neither is the line significant ($p =$

0.599) (Table 4-10). Hence there is no significant trend in the Tall Moss cover along a piosphere gradient.

Table 4-10. P-values of the statistical analysis for fitted line for total Tall Moss cover

Model	Linear	Deviation
Linear	0.599	0.858
Equation of fitted line	...	

Tall Mosses have a specific habitat or sensitivity, particularly near the south and south-east of the canopy of shrubby plants (not directly under the canopy) and have small overall mean percentage cover, less than 0.45 (0-0.7)%. Moreover, there is zero cover of this group at some sites. For example in five out of six sites in Corio paddock there was no observation of this group (Figure 4-11).

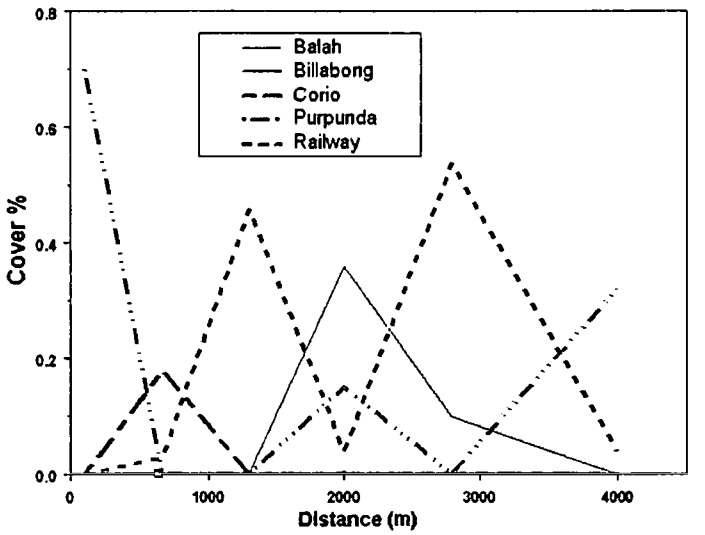

Figure 4-11. Tall Mosses cover profile in different distances of water in five paddocks at MFC

4-6. Discussion

4-6-1. Comparison of Site Productivity Potential with BSC Cover Variation Along the Defined Transects

In considering the concept of site productivity potential (Tongway & Smith, 1989; Tongway, 1994, 1995b), we can not expect 100% BSC cover on the study sites because of the area covered by vascular plants, and also because of other features such as eroded areas, which create limitations for the establishment or stability of BSC. It should be noted that stratification was not 100% successful in locating all sites in similar vegetation communities and nearly 13% of the sites were selected in woodland or 43% in mixed woodland-shrubland communities which have a negative relationship with BSC distribution (Ch.3). A methodology such as an effective

stratification which can remove these environmental variations can increase the significance of relationships between BSC cover and degradation. Thus from these results, it can be concluded that a productivity potential of the study paddocks for BSC cover is about 36.99%. On the other hand, at 100 m sites BSC cover ranged from 0.2 to 5%, which showed that their current condition is much less than their potential BSC cover. Maximum BSC cover in the sacrifice zone (100 m) is less than 10% with a mean of 1.69% confirming Graetz and Ludwig's (1978) study. Thus sites at 100 m have lost almost 22% of their BSC cover. These results are important if compared to percentage cover of the perennials and total vascular plants in Appendix C-1. In 80% of all sites perennial and total vascular plant cover was less than 20%. Moreover 84% of the sites have less than 10% annual plant cover, 57% of sites had litter cover less than 10% and 43% of sites between 10 to 15%. Therefore, BSC cover, after bare ground, is the second largest land cover at MFC and a significant indicator of trampling pressure if pre-assessment issues are considered.

4-6-2. Discernable Piosphere Patterns of BSC Cover

A grazing gradient BSC cover is discernable for up to 2000 to 3000 m distance from watering points, and after that, although there is a gradual trend between the sites at 2000 m to 4000 m, variations are very small, which is mostly related to micro-scale site characteristics and BSC cover variation rather than trampling pressure. Number of tracks and dung distribution are also dramatically decreased at sites further than 2000-3000 m from the watering points (3-9-3), indicating that a 2000 m transect line for gradient identification for BSC study would have been sufficient at MFC, supporting the results of Graetz and Ludwig (1978). However, it should be noted that this length of transect may have to be varied where different stocking numbers are used.

4-6-3. BSC Cover is an Indicator of Rangeland Condition

BSC provide a beneficial role in the landscape, largely through the process they mediate, in particular nutrient cycling, infiltration and erosion (West, 1990; Eldridge & Koen, 1998). Consequently BSC cover might be expected to equate with a more stable and healthier landscape (Eldridge & Koen, 1998). Results of this chapter show that total BSC cover, including all groups except Tall Moss cover, have significant relationships with trampling pressure at MFC. Results show that BSC cover changes from 1.69% (100 m) to over 36.99% (4000 m) in contrast to previous research showing cover variance of BSC in the piosphere framework as less than 10% (Anonymous cited in Rosentreter & Eldridge, 2002). Results support Graetz and Ludwig (1978) who reported more than 15% BSC cover change along their piosphere gradients. These changes

under trampling pressure show that BSC are a good indicator of rangeland degradation supporting Kleiner & Harper (1977) and Klopatek (1992). However, the results are in contrast to some more recent literature concluding that BSC cover is a weak indicator of a grazing response (Eldridge & Koen, 1998; Rosentreter & Eldridge, 2002). It is believed that insignificant relationships are due to the fact that landscapes recovering from degradation may be dominated by cyanobacteria or cyanolichen such as *Peltula* spp. whilst similar cover levels at less degraded sites are dominated by grazing (trampling) sensitive species such as foliose or fruticose lichens. This thesis was not a long-term study to conclude or compare these sorts of results in the recovery process, however, results showed the significance of BSC cover change as a robust indicator of rangeland condition, given some preliminary considerations such as stratification and use of a suitable sampling method.

4-6-4. BSC Morphological/ Functional Group Cover Variations under Grazing Pressure (Trampling) in the Piosphere Framework

Some BSC species appear more tolerant to trampling (Rogers & Lange, 1971; Eldridge, 1998c; Eldridge & Rosentreter, 1999; Rosentreter & Eldridge, 2002). This is probably due to differences in their morphologies, as foliose or fruticose forms seem to be more susceptible than crustose and squamulose forms (Eldridge & Rosentreter, 1999). Thus, apart from their roles in assessing diversity, BSC groups can provide valuable information about the health and recovery of ecosystems (Eldridge & Rosentreter, 1999).

MFC is a lichen-dominated rangeland and the Black Common Lichens (BCL) group is the dominant group amongst the lichens. BCL with 62% of total BSC cover under light grazing (Lange *et al.*, 1984) shows a significant response to location in the piosphere. There is little support from literature for this group as being a good indicator of rangeland condition (Eldridge & Koen, 1998; Eldridge & Rosentreter, 1999). Eldridge and Rosentreter (1999) classified most of the BCL species as a weak indicator of landscape health. Eldridge and Koen (1998) classified brown squamulose lichens such as *Endocarpon* spp. and black gelatinous lichens such as *Collema* spp. with a moderate and low value for rangeland condition. These are the main species of BCL group at MFC (3-10). Eldridge and Koen (1998) defined most of the species of BCL as ubiquitous (grazing-tolerant) species and these results support their claim because BCL appear in all landscapes, even near water points. However, results show that their percentage cover varies from a mean of 1.05% at sites 100 m from the watering point to a mean of 20.08% at 4000 m sites, a factor of 19. This confirms that although this group is more habitat tolerant than other lichen groups, indicating that they are sensitive to trampling and thus are a good indicator of rangeland condition.

Scaly Lichen is the second dominant group among the lichens at MFC with percentage cover varying from a mean of 0.1% at 100 m sites to 5.6% at 4000 m a factor of almost 56%, showing that this group is a significant indicator of rangeland conditions. According to the rate of change along the piosphere gradient, their value as an indicator of rangeland condition is higher than the BCL. These results support Eldridge and Koen's (1998) results showing that Scaly Lichens such as *Fulgensia* spp. were associated with stable landscapes in good rangeland condition with enhanced nutrient status.

As reviewed in Section 4-5, Leafy and Crusty Lichens and Tall Mosses percentage cover at MFC is very low (less than 2%). Previous studies emphasized the relationship between degradation and Leafy Lichens (Eldridge & Koen, 1998; Eldridge & Rosentreter, 1999) and the absence of this group at the 100 m in five paddocks support this claim. In contrast, at 4000 m sites the cover of this group was a mean of 0.88%. Results support Eldridge and Koen's (1998) results where Leafy Lichens are associated with stable landscapes in good conditions with enhanced nutrient status. Moreover Eldridge and Rosentreter (1999) also emphasized the significant relationship between this group with rangeland conditions. In comparison with either BCL or Scaly Lichens this group is more sensitive with almost 88 times more cover variation between the 100 m and 4000 m sites.

Crusty Lichen has low distribution, particularly around the watering points with a mean of 0.006% at 100 m sites in comparison with 0.84% at 4000 m sites, a factor of 140, indicating that they are highly grazing-sensitive. These results are in contrast to those of Eldridge and Koen (1998) and Eldridge and Rosentreter (1999) who concluded that this group has low to moderate value for rangeland condition assessment.

As concluded in Section 3-10 mosses can be classified in two distinguishable groups based on their habitat or sensitivity characteristics: Black Common Mosses (BCM) and Tall Mosses. BCM is the second dominant group at MFC and shows a significant piosphere gradient with a mean of 0.47% at 100 m sites to 7.8% at 4000 m sites, a factor of 17. These results contradict West (1990), and Eldridge and Rosentreter (1999) stated that mosses are grazing insensitive.

Tall Mosses are distributed on the southern and eastern sides of vascular shrubby plants. This group with 0.45% cover has very mixed patterns without any significant piosphere gradient observed. This result was unexpected because it is accepted that they are very sensitive to trampling because of their morphology. There may be environmental factors controlling the distribution, but nevertheless from the results of this study, Tall Moss has low value as an indicator of rangeland condition in comparison with lichens.

4-7. Conclusions

BSC cover is a significant indicator of rangeland degradation if sites are stratified prior to sampling and samples collected by line-intercept. Total BSC, total lichen, total moss and all BSC groups except Tall Mosses increase significantly as distances increase from water. Potential expected BSC cover in the shrubland community at MFC is about 36.99% but sites at 100 m distance from water have lost almost 22% of their potential cover. Discernable piosphere gradients for BSC in the study area occur within 2000-3000 m from watering points. Lichens are more sensitive than mosses as an indicator. Among the lichen groups Crusty and Leafy Lichens are more sensitive and have higher value as an indicator of rangeland condition.

CHAPTER 5

5. GROUND-LEVEL SPECTRAL CHARACTERIZATION AND INDICES TESTING FOR LATER USE IN MULTISPECTRAL REMOTE SENSING

This chapter
Ground-level spectral characterization of objects on the ground for multispectral and hyperspectral remote sensing is the base step for understanding and developing a suitable method for land cover analysis. This chapter aims to characterize the spectral signature of different BSC groups in comparison with non-BSC land cover components in both dry and wet conditions for multispectral datasets such as Landsat TM imagery. Moreover, by considering commonly used indices such as the PD54, SSI and NDVI in Australia, they were tested using synthesized spectra for Landsat TM imagery. This chapter provides the necessary basis for the ground-level spectral modelling in Chapter 6 and remote sensing analysis in Chapter 7 for BSC detection.

5-1. Introduction

Ground-level spectral characterization and indices testing using the synthesized spectra for a given sensor are the base steps for understanding and developing a suitable remotely-sensed method for multispectral and hyperspectral remote sensing. However, despite the creation of spectral libraries for various materials and vascular plant species (USGS, 2004; JHU, 2005; JPL, 2005), and many local studies for spectra characterization and indices testing in different parts of the world (Billings & Morris, 1951; Pearman, 1966; Gausman & Allen, 1973; Ehleringer, 1981; Price, 1992; Bastin *et al.*, 1993a; Bastin *et al.*, 1993b; O'Neill, 1994a; Price, 1994; Karnieli, 1997; Lewis, 2002a; Richardson *et al.*, 2004) the unique identification of many materials has proven difficult due to the numerous problems present in the real-world measurements, such as angle of view, atmospheric properties, spectral mixture, moisture content and illumination angle, to name only a few (Milton, 1987; Clark, 1999; Milton, 2001). Furthermore, Price (1994) has suggested that several species may actually have quantitatively similar spectra due to the spectral signature variation present within a species. In brief, spectral signatures may not be unique (Price, 1992; Price, 1994). In addition, well known spectral libraries such as the United States Geological Survey (USGS, 2005) and Jet Propulsion Laboratory (JPL, 2005) gave little consideration to the BSC spectra. Finally, BSC effects on the commonly used indices such as the PD54, SSI and NDVI on the area in which BSC are common were less considered.

5-2. Review of Relevant Theory and Research

5-2-1. Application of Spectrometry in Remote Sensing

One of the principal uses of remote sensing technology is the direct or indirect measurement of biophysical properties of the Earth's surface (Jensen, 1983). Thus, spectral standards are fundamental to all multispectral and hyperspectral remote sensing projects and interpretations. Such data often provides the basis for remote sensing work conducted on broader scales, such as those monitored by modern Earth-observing satellites. Understanding the basic principal of spectrometry such as specular; diffuse (Lambert's law) reflection (Campbell, 2002); intermediate cases and reflectance types (i.e. directional, conical and hemispherical); albedo, and absorption (molecular rotation, lattice vibration, electronic transitions and free carriers) is important to develop a concept and methodology of spectral characterization for multispectral and imaging spectrometry (Lillesand & Kiefer, 2000).

An important application of spectrometry is its use in the calibration and validation of data from airborne and space borne sensors (Clark, 1995; Clark, 1999; Milton, 2001). Accurate calibration of remotely-sensed data to surface reflectance is a requirement of most analytical procedures and there are a number of ways in which this can be achieved. In the simplest method, often referred to as the "Empirical Line Method" (Milton, 2001), simultaneous with image acquisition, field spectral measurements are made at a number of extensive, spatially uniform ground targets and a linear regression model derived to relate the reflectance measured at the ground to the radiance measured by the remote sensor. A number of remotely-sensed methods are initially developed or simulated by ground collected spectra (Pickup *et al.*, 1993; Pickup & Chewings, 1994; Rundquist, 2002; Karnieli, 2003).

This study was conducted to acquire and characterize laboratory and field spectral samples, which serve as standards for the interpretation of remotely-sensed data. Land cover components must be analysed and characterized for inclusion in the spectral data base. Although some studies from nearly 25 years ago examined how each component of land cover contributes to the overall reflectance (Graetz & Gentle, 1982; O'Neill, 1994b; Clark, 1999; Rundquist, 2000), there is little information and understanding of the spectral characteristics of BSC in the rangelands of Australia (O'Neill, 1994b). To date, it has been difficult to definitively identify BSC because of their complex spectra, small size and similar spectral patterns to bare soil and vascular plants (O'Neill, 1994b; Karnieli & Tsoar, 1995; Karnieli & Sarafis, 1996; Karnieli *et al.*, 1996; Karnieli, 1997).

5-2-2. Concept of Spectral Characterization

For land surface components, visible and NIR reflectance spectra are the product of complex patterns of scattering and absorption by numerous structural and biochemical components (2-8-1). Pigments (e.g. chlorophylls and carotenoids) directly absorb visible light energy as the first step in photosynthesis, whereas other compounds (e.g. starch, protein and carbohydrates) are characterized by NIR absorption signatures which are a consequence of stretching and vibration by the C-H, N-H and O-H groups of which they are composed (Richardson *et al.*, 2004). Interpretation of reflectance spectra is difficult at best, because although the spectral characteristics of the different components are unique, they are also broad and thus frequently overlap (Curran, 1989).

The focus of biophysical remote sensing is usually the investigation of land condition. This task includes spectral signature description; chlorophyll absorption characterization; biomass and Leaf Area Index estimation, and water content measurement (Jensen, 1983). The importance to remote sensing of each of these tasks has been demonstrated at many spatial, spectral and temporal resolutions. Almost all remotely-sensed methods collect some land cover spectra to connect these data with the spatial and spectral resolutions of remotely-sensed data.

5-2-3. Spectral Variation and Characterization of Vascular Plant

Early studies that explored spectral differences between taxonomic and ecological groups of vascular plant species reported on overall similarity in visible and NIR optical properties between arid and semi-arid plants and a wide variability within taxonomic and functional groups (Billings & Morris, 1951; Ehleringer, 1981). However, studies that have conducted quantitative rather than descriptive approaches to analysis and comparison of spectra have noted that there are strong ecological and taxonomic differences in the leaf spectra of vascular plants (Lewis, 2002a). For example, Gausman and Allen (1973) identified significant statistical differences between the reflectance of cultivated plant species at seven visible and NIR wavelengths. Austin *et al.* (1993) found significant differences between the visible spectra of different species, even within a genus. Within species differences in biochemistry and reflectance appeared to vary by life stages and by season more than between species at any given time. Differences in the shape of the chlorophyll-absorption features between several species of conifer have been demonstrated (Clark *et al.*, 1992; Gong *et al.*, 1997). Skidmore and Schmidt (1998) showed several significant differences between reflectance of eight African grasses, with most discrimination between species occurring in the visible red and 1300 nm NIR regions. Asner *et al.* (1998) found significant differences in visible and NIR reflectance between grasses and a group of tree and shrub spectra from savannah ecosystems in

the south-west of the USA but did not find differences between tree and shrub growth forms. Cochrane (2000) was able to discriminate 11 species of tropical forest trees with accuracies of 80–95%. Overall, as these early studies have reported, differences between taxonomic and ecological groups of vascular plants do exist, but there is wide variation within taxonomic and functional groups, so that overlapping data create difficulty in the discrimination of spectral types.

There have been relatively few studies of the spectral properties of Australian vascular plants (Lewis, 2002a). The Australian flora shows widespread adaptation to aridity and limited soil nutrients. Evergreen sclerophyllous plants characterized by reduced leaf area, increased tissue thickening, and radiation-reducing leaf coatings, dominate many Australian temperate and semi-arid ecosystems, and much of the Australian arid zone carries semi-succulent perennial shrubs from the Chenopodiaceae family (Wilson & Graetz, 1979; Lewis, 2002a). Lewis (1998) reported that Australian arid landscapes, particularly in their dry state, typically lack spectral variability, with most differentiation related to soil brightness and vegetation cover. Lewis also noted that many Australian native grasses have summer growth patterns that contrast with the winter growth of introduced Mediterranean plants. This difference in phenology is echoed by their spectral response throughout the year.

5-2-4. Spectral Variation and Characterization of BSC

There have been some studies in different parts of the world, particularly in Israel, to characterize spectral variation and compare spectra of BSC with that of bare soil (Karnieli & Sarafis, 1996; Karnieli *et al.*, 1997; Karnieli *et al.*, 1999). Other studies have been conducted for spectral characterization of rock-based and arctic soil crusts (Solheim *et al.*, 2000; Bechtel *et al.*, 2002). Karnieli *et al.* (2001) reviewed BSC spectral characterization literature, particularly in Israel, and concluded that the cyanobacteria-dominated soil spectra curve is higher in the visible region than that of vascular plants and is similar to that of soil however, the NIR region spectral patterns are more complex. Karnieli and Sarafis (1996) from laboratory analyses of dry and wet cyanobacterial soil crusts described absorption peaks due to phycoerthrin in the 580 nm band and absorption caused by phycoerythrin at 630 nm. They also described that because of the blue reflectance maximum at 430 nm, this wavelength is valuable in the detection of BSC in the Negev desert. Later Karnieli (1997) described a way to classify dune sand by means of a Crust Index (2-10-4). Karnieli (1997) and Karnieli *et al.* (2002) suggested that the special phycobilin pigment in cyanobacteria contributes to producing a higher reflectance in the blue spectral region (450-520 nm) than the same type of substrate without the BSC. Karnieli *et al.* (2002) reported that the spectral reflectances of soil crusts

vary among geographical regions. Laboratory collected spectra in the USA showed an absorption feature at approximately 680 nm due to chlorophyll *a* present in BSC organisms (Karnieli *et al.*, 2001). Karnali *et al.* (2001) noted that the spectral characteristics of BSC in the USA were similar to the spectra of soil crusts in the Negev desert.

Since the early 1980s, studies have emphasised the importance and effect of BSC on spectral signals received by satellite and airborne sensors, particularly in the chenopod shrublands of Australia (Green, 1986; Graetz *et al.*, 1988), but was not considered in practical remotely-sensed methods. Some studies (Cameron & Lewis, 1996; Lewis, 1998; Lewis, 2000) used remote sensing in areas where BSC were common, such as those at MFC and Fowlers Gap in New South Wales, but without clear spectral analysis and understanding of the BSC spectral characteristics. Although some studies have revealed the unique spectral features of BSC (O'Neill, 1994b; Karnieli *et al.*, 1999; Karnieli *et al.*, 2001; Chen *et al.*, 2005) only a few studies have made use of one or two spectral features of these components. For example, Lewis *et al.* (2001) used BSC spectra as one group for endmember selection and Filders (2004) used two lichen groups for endmember selection. O'Neill (1994b) investigated a BSC spectral characteristic based on taxonomic groups such as mosses, lichens and cyanobacteria on two soil types with different moisture conditions and found that the presence of BSC on both soil types decreased reflectance throughout the spectrum. O'Neill also found that a strong photosynthetic response occurred within ten minutes of wetting. But it is significant that most of these studies in Australia (Grierson, 1998; Grierson & Lewis, 1998; Lewis, 1998; Lewis, 2000), where BSC occur, gave little consideration to BSC in their remotely-sensed methods. Overall, there are few attempts to characterize and use BSC spectra, particularly to BSC group level. Therefore, there is still considerable scope for new studies of the spectral responses of BSC, particularly at the BSC group and species level, and in comparing their response in dry and wet (photosynthetically active) states.

Overall, there are some ambiguities within the literature. Some claimed that the spectra of dry BSC are similar to that of bare soil (Karnieli *et al.*, 1996; Karnieli *et al.*, 1999; Karnieli *et al.*, 2001; Karnieli, 2003). Others interpreted images without consideration of BSC (Cameron & Lewis, 1996; Lewis, 1998) and some have identified BSC as a detectable endmember by hyperspectral remote sensing (Lewis *et al.*, 2001; Fildes, 2005). All of these studies have selected imagery when BSC were dry. Less information exists about the extent and spectral characteristics of BSC, particularly the various groups of BSC compared with the other land covers and how their spectral characteristics respond to wetting.

5-3. Aim of Chapter

The main objective of this chapter is to systematically analyse the visible and NIR regions of the spectrum, by simulating multispectral imagery such as Landsat TM for spectral characterization. However, before simulating spectra for TM imagery, a whole range of 430 to 900 nm spectra was considered by plotting the spectra of different objects versus each other for visual examination of the similarities and differences. This study takes one step further on the spectral analyses of BSC in the group level to compare and investigate the existing variations within and between the defined groups. The spectral features of BSC relative to rangeland surface features (vascular plant, bare soil, stone, litter and shadow) in the field in both dry and wet conditions were considered for spectral characterization. Six BSC groups (3-10) and one "BSC pattern spectra" were considered in comparison with the other land covers to compare variations within and between the groups by visual interpretation of plotted hyperspectral signatures and by examination of simulated multispectral data space. Various indices such as the PD54, NDVI and SSI were compared. An important objective was to compare dry spectra and wet spectra as a possible solution for detecting BSC using multispectral remote sensing data. The aim of spectral characterization was to set up the role of the BSC in the vegetation and soil stability indices such as PD54, NDVI and SSI which have been widely used in Australia for rangeland monitoring. Specifically, the following objectives were considered:

1. To characterize spectra for the possibility of detecting BSC in dry and wet conditions
2. To examine the effects of dry and wet BSC in the remotely-sensed data and existing indices.

5-4. Methods

5-4-1. Spectrometer

Spectrometers have been used with varying success for different applications. These instruments are usually ground-based and can be used in laboratory or field conditions, depending on the make and model. In this study a UniSpec spectrometer (PP Systems, 1999) was used, which is self- contained and field-portable. It features a high resolution spectrometer, photodiode array detector and integral halogen sources (PP Systems, 1999). Hemispherical reflectance measurements in the visible and NIR wavelength region of the EMR (350 to 1100 nm) were made by this spectrometer at a field of view of a foreoptic the 42 and 3 degrees. The visible / NIR portions of the spectrum had a spectral

resolution of approximately 3.3 nm (PP Systems, 1999). For more details of the UniSpec spectrometer, See Appendix F-1.

5-4-2. Spectral Measurement

5-4-2-1. Viewing Geometry

Radiance and irradiance vary in zenith and azimuth (Milton, 1987). Thus to specify completely the reflectance field at the target, the reflectance must be measured at all possible source/ sensor positions, resulting in a bi-directional reflectance distribution function (BRDF). There are tremendous variations in the spectral properties of different land covers due to composition, size, and mixture types. One of the possible influencing factors is viewing geometry, including the angle of incidence, angle of reflection, and the phase angle which is the horizontal angle between the incident light and observer that all effect the intensity of light received. Varying the viewing geometry results in changes in shadowing and the proportions of multiple scattering (Milton, 1987; Clark, 1995; 1999; Milton, 2001), which can effect band depths a small amount except in rare cases. While measuring precise light levels are important for processes like radiation balance studies, they are of lesser importance in spectral analyses. The selection of an appropriate viewing geometry depends upon whether the spectra are used for image analysis or for a feasibility study. For image analyses, a viewing geometry similar to that of airborne and/or space borne sensors is required. For a study, it is possible to eliminate much of the variance present in an image data set by fixing the viewing and illumination geometry. The viewing geometry for this study was considered for feasibility study and image analyses according to Figure 5-1.

5-4-2-2. Spectral Measurement

Spectral measurements were made for perennial plants, annuals (grasses and forbs), litter, bare soil, stone and BSC (groups). Likewise, different species of BSC were collected in Petri dishes and labelled 1, 2, 3, etc in the field for consistent identification of the different taxa for future laboratory spectral measurement. Measurements were recorded in radiance mode (as opposed to reflectance) at an average of 10 to 20 scans in order to minimize instrument and different objects noise. Integration time (PP Systems, 1999) was set up on 3 seconds and an average to scan was also set up on 3. Radiance measurements were collected in the visible and NIR regions simultaneously and with the same integration times, to maximize the signal-to-noise ratio of each measurement. Immediately before acquisition, incident radiation on the object was observed by measuring the up welling radiance from a dark current and from a Spectralon white reflectance panel (PP Systems, 1999).

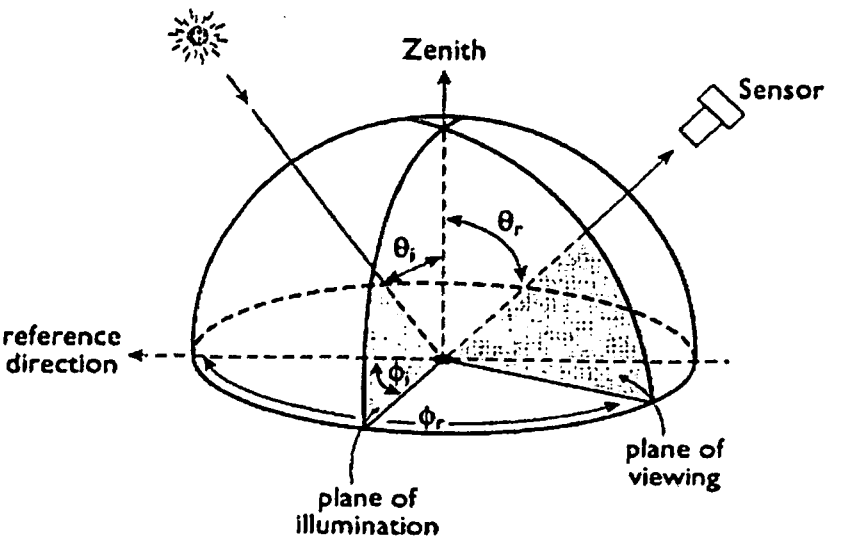

Figure 5-1. Definition of the angles involved in field spectroscopy, for sensor, sun angle and position (Kriebel, 1976)

In post-processing the collected radiances were divided by the Spectralon panel radiance spectra to determine object reflectance (as a percentage of incident light). In both field and laboratory measurements, the spectrometer was pointed downward above the target. The observers and frame were always positioned on the south side of the plot to avoid casting shadows into the Instantaneous Field Of View.

5-4-3. Field Spectra Sampling

All of the spectra sampling were made in days with a clear atmosphere during June 2003 to June 2005 (Appendices E-2 & F-2). The collection of pure spectra was performed by stacking an optically dense pile of specimens and this study tried to keep the original structure of the vascular plants and BSC, when spectral sampling. The measurements were conducted in an open and well illuminated area close to the collection site, taking into account all the precautions such as cloud and wind free days for spectral sampling; bare soil moisture content; dark clothes of researcher; peak sunshine (hours11:00 am to 3:00 pm); and weather data [Bureau of South Australiain Meteorology (2005), Appendix F-2] that have been described in literature (Milton, 1987; Curtiss & Goetz, 1994; Salisbury, 1998; Milton, 2001). To cover the natural variability, several measurements (more than 10) were made in each pile of specimens, by pointing at different zones by the same geometry (Figure 5-1). Notes were made to record anything of interest to do with sample appearance and

condition. All spectra were collected under dry conditions, then wet spectra of the same sample were collected at the same situation. The samples were wetted until the wetting depth reached at least 10 mm (O'Neill, 1994b) and then spectral data of wet objects were collected. For shadow data there was very high variation from under a plant, such as *Acacia* spp. with a sparse canopy to the other species such as *Maireana* spp. with a dense canopy. Shadow spectral data under objects of different plants were collected. Litter also has extreme spectral variation, visible as colour variations.

5-4-4. Collection of "BSC Spectral Patterns" (in the Field)

This part of the study was plot-based to measure BSC on the site or with background soil, rather than as individual species or morphological /functional groups. For site or plot selection some criteria such as priority or importance of BSC group and total cover of them were considered. According to the results of the classification of BSC groups, black components (black lichens + black mosses) cover more than 82% of the study sites (3-10). Moreover, percentage cover of BSC was nearly 1.69% in degraded sites to 36.99% in undegraded conditions (4-5-3). Thus, two groups of plots were selected. The first group of plots was selected without BSC (less than 1%). The second group was selected and was representative of undegraded conditions with at least 30% BSC cover. These plots were selected to have a percentage cover of black components (lichens + mosses) of more than 80% of total BSC cover. Figure 5-2 shows a schematic view of pattern data collection at the plots. The ground coverage corresponding to an Instantaneous Field of View of 3°, from 50 cm distance, was less than 10 cm in diameter, so spectral data were collected inside the defined 50 × 50 cm plots.

5-4-5. Laboratory Sampling of BSC Spectra

Following existing literature (Karnieli *et al.*, 1999; Solheim *et al.*, 2000; Bechtel *et al.*, 2002; USGS, 2004), this study used an external light source of a 1000 W Tungsten Halogen collimated lamp as the light source for laboratory experiments. There is no agreement for the angle and distance of the light source from the sample in the literature. For example, Solheim *et al.* (2000) used the lamp at its maximum beam aperture opening of 39°, and 130 cm distance for detecting target. The source beam was centred on the centre of the target platform, for $\theta_s = 30°$. Karnieli *et al.* (1999) positioned the lamp at 45° zenith angle and the optical head was installed about 0.5 m above the sample, at nadir. Although lichens and mosses do not have considerable shadow effects, in order to avoid the very small shadow effects of Leafy Lichens at different zenith angles, this study concluded that the 45°

angle had the best results for this study by checking dark object and white panel spectra under both sun and artificial illuminations.

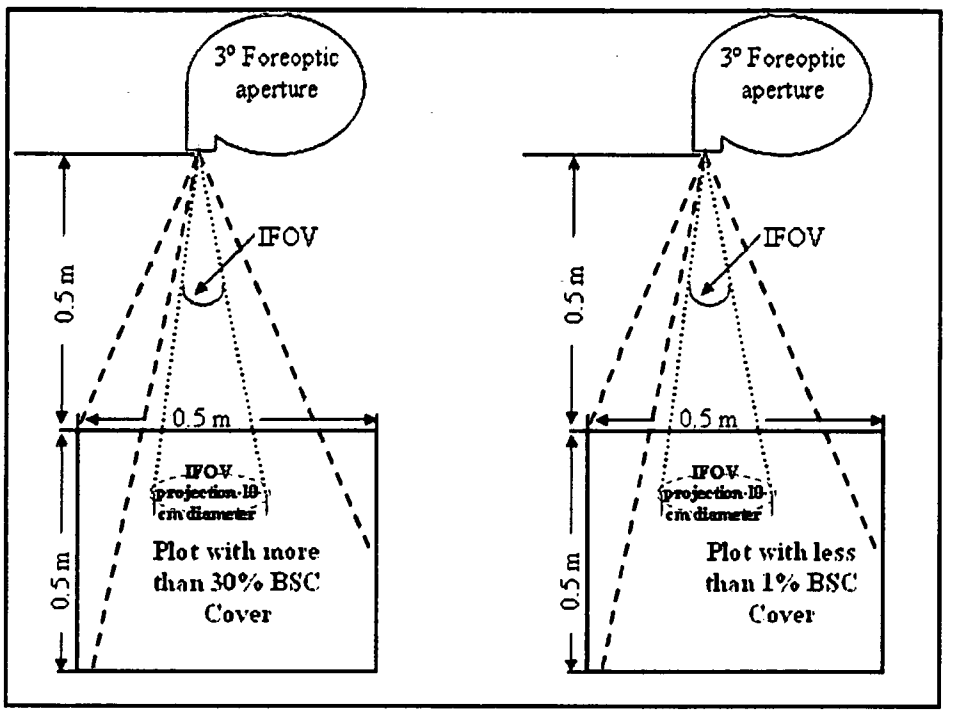

Figure 5-2. Schematic view of the plot-based spectra collection for pattern analyses

Spectra of soil and BSC samples, free of vascular plant material and litter, were collected by scraping the soil surface to 1 cm depth. The samples were stored in Petri dishes and were kept in an outdoor, natural environment with direct sun, and exposed to wind and rain. The collected specimens were sampled a short time after data collection for the first repetition. However, these specimens were re-sampled another two times, which was too long from the specimen collection time. Collected specimens were laid on a matt black coated board to minimize the external reflectance and backscatter. A 10 cm Petri dish target holder was spray-painted black, inside and out. BSC specimens were aligned with the top edge of the Petri dish. The floor of the specimen location was also covered with matt black cardboard. Because of the low height of the specimens, except for *Chondropsis semiviridis* and *Xanthoparmelia* spp., there was no internal shadowing during the sample collection. For the mentioned species, careful sample preparation was undertaken. However a little shadow in the background of specimens was inevitable. After dry spectral data collection, all components were wetted to saturation stage and then spectral data of wet BSC were collected.

5-4-6. Data Pre-processing

In Sections 5-5-1, 5-5-2 and 5-5-3 a whole range of the dataset from 430 – 900 nm is used for visual presentation of similarity and dissimilarity between BSC groups with other land covers. In this, and subsequent chapters, re-sampled synthesized TM bands data were used for different analyses as described below. Collected raw spectral data ranges (350 - 1100 nm) were calculated as reflectance data (PP Systems, 1999) and imported into an Excel spreadsheet for further analyses. Individual spectra of each object were plotted and examined to ensure no erroneous data were incorporated in subsequent analyses. Collected spectra with 3.3 nm intervals were used for spectral characterization of BSC and different land covers to outline the differences and similarities of the spectral patterns under both wet and dry conditions. Due to the presence of several noisy channels, the data were cropped to a range of 430–900 nm. After this data sub-setting, the spectra were partitioned into four sets comprising bands 1 (450 - 520 nm), 2 (520 - 600 nm), 3 (630 - 690 nm) and 4 (760 – 900 nm) of TM imagery.

5-4-7. Extraction of Mean Spectra

A number of collected spectral data for different land covers and BSC groups are presented in Table 5-1. These data were used for mean reflectance with standard error calculation and for final presentation and index calculation.

5-4-8. Plotting Different Spectra of Land Covers

Collected field samples included dry and wet spectra for different objects with a minimum nine samples for Black Common Mosses in wet conditions and maximum 252 samples for woody plants (spectra of different plant species were collected) (Table 5-1). To understand the location and distribution of different rangeland covers in the data space of TM bands, field-collected spectra from different objects were plotted by the selection of different bands versus each other. Then the best plots were selected for detailed study of BSC groups by examining the data space for each land cover.

5-4-9. Perpendicular Vegetation Index (PD54)

This study used the measurement concept between the soil and vegetation lines (2-10-3) of red versus green bands of TM imagery. When the vegetation fraction is near zero the plotted point should be near or on the soil line. When the vegetation fraction reaches 100% the plotted point should be near or on the vegetation line. Points that are near or on the soil line, and that have low

reflectance, correspond to dark soils. Points that are near or on the soil line have high reflectance correspond to light-coloured soils. The same is essentially true for vegetation: those canopies that are bright, such as vigorous *Atriplex vesicaria*, *Maireana* spp., *Acacia* spp. and some annual and herbaceous plants will be located at the end of the vegetation line having high reflectance.

Table 5-1. Main land covers and BSC groups which were used in this chapter for spectral characterization, and the number of spectral samples for each group

Land covers				Dry dataset (spectra), n =	Wet dataset (spectra), n =
Bare soil				108	75
Stone				40	18
Litter				41	15
Shadow (bare soil under dense and sparse canopy)				35	20
Photosynthetic components	Vascular plants	Perennials*	Woody plants*	252***	252***
			Herbage*	21***	21***
		Annuals		14***	14***
	BSC groups	Black Common Lichens (BCL)		77	12
		Black Common Mosses (BCM)		51	9
		Scaly Lichens		71	13
		Leafy Lichens		71	25
		Crusty Lichens		46	10
		Tall Mosses		46	10
BSC patterns**				26	15

* in some sections woody plants and herbage were separately measured and in some sections perennials were merged with the spectra of woody plants + herbage
** BSC patterns + bare soil background were measured from 50 cm above given plots by the dominance of black BSC components
*** the same spectra for dry and wet conditions were assumed

It should be noted that the vegetation and soil lines tend to be non-parallel in both spectral spaces: the slope of the vegetation and soil lines are slightly less than that of the soil line. Vegetation fraction estimates depend upon both soil brightness and vegetation greenness. This divergence depends also on the relative positions of the soil and vegetation lines (Gitelson *et al.* 2000). In this study, band 3 versus band 2 of simulated TM imagery was considered for the PD54 consideration.

5-4-10. Land Cover Components in the TM Data Space for Dry *vs.* Wet Conditions with Band Combinations or Fractions

From the existence developed indices, NDVI, which uses band fraction to define vegetation cover and SSI, which uses band combination in the Cartesian data space to define the soil stability, were considered to examine the data cloud patterns of BSC in comparison with other land covers.

5-4-10-1. Normalized Difference Vegetation Index

The general concept of the NDVI is reviewed in Section 2-10-1. NDVI is formulated as:

$$\text{NDVI} = \frac{\rho NIR - \rho R}{\rho NIR + \rho R} \qquad \text{equation 5-1}$$

where ρ is the reflectance value in the indicated spectral bands. Values of the NDVI range between –1.0 and +1.0 but are usually positive for soil and vegetation. Denser and/or healthier vegetation will have higher values. NDVI values for vegetation usually offer the means of efficient and objective evaluation of phenological characteristics (Justice *et al.*, 1985; Reed *et al.*, 1994). In this chapter a fraction of ρNIR-ρR versus ρNIR+ρR was considered in the Cartesian data space to define the cloud of BSC spectra.

5-4-10-2. Soil Stability Index

The general concept of the SSI is reviewed in Section 2-10-2. SSI is based on the band combination and its equation for MSS and TM data formulated as:

For MSS: (Band 2 / Band 3) *vs.* (Band 1 / Band 3) equation 5-2

For TM: (Band 3 / Band 4) *vs.* (Band 2 / Band 4) equation 5-3

This thesis examined this index as an example to determine the effect of BSC in the data space of TM imagery.

5-5. Results

5-5-1. Spectral Complexity and Variation in the Rangeland Ecosystems

As previous studies have noted (Price, 1992; Gong *et al.*, 1997) , large variations exist between the spectra of major land covers such as bare soil, vegetation, rocks and minerals. The following section illustrates the variability of spectral reflectances of rangeland features at MFC.

5-5-1-1. Spectral Variations within a Single Object

The first example (Figure 5-3), is dry bare soil with two soil colours, which were measured in different sites and classified using a Munsell Chart in the field (3-9-2). There is very high spectral variation, particularly in the NIR bands for two soil colours. The variation is much higher than the presented graph for soil properties, if texture and other colours and characteristics are considered. The second example is for one woody plant species (*Maireana sedifolia*) at different growth stages and under different grazing pressures (vigour, senescence, ungrazed and grazed) (Figure 5-4). The variation for only one species on the same day is very high (more than 30% variation), thus, potentially generating difficulty for use of remotely-sensed data for rangeland monitoring and hesitation about the accuracy of remotely-sensed methods.

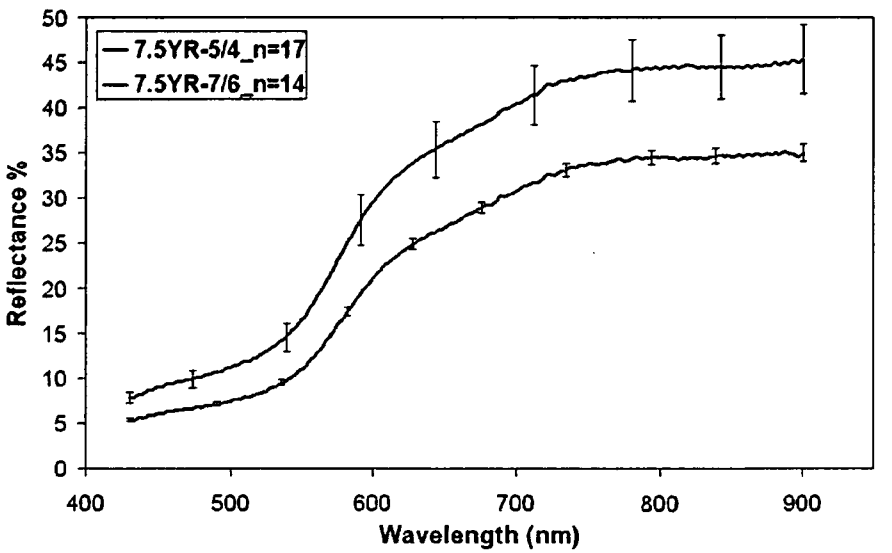

Figure 5-3. An example of spectral variation for soil with two colours (Munsell chart / Hue, Value and Chroma) at different times of a year (the procedure of spectral measurement such as viewing geometry, distance between foreoptic and samples were the same for all samples) at MFC (presenting the existing variation for one object)

5-5-1-2. Dry Spectra of All Land Covers at MFC

Figure 5-5 shows dry field spectra of different land covers at MFC. Inclusion of all components on one pixel of TM-like (30 m) imagery is common on the arid and semi-arid rangelands such as those at MFC. From this graph, the mixture and complexity issues of spectra for different land covers on the same pixel are considerable. In spite of these complexities, according to the spectral patterns particularly in "red edge", there is some important potential for discriminating different land covers from each other. Overlapping and ability to discriminate BSC groups is described in Section 5-5-2.

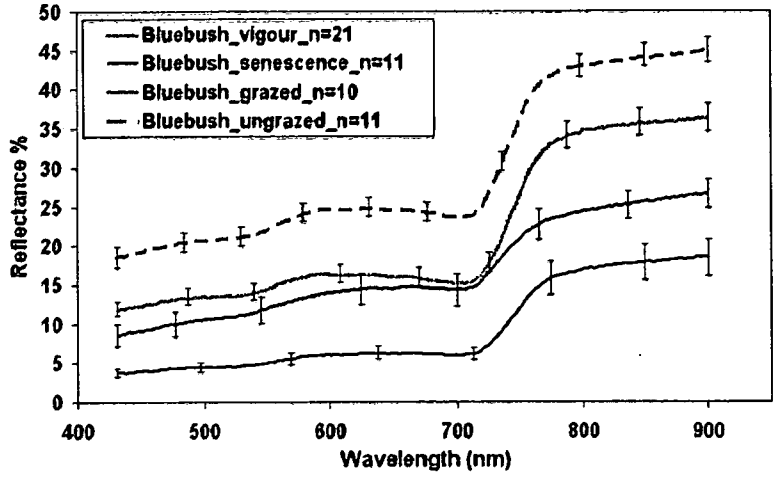

Figure 5-4. An example of spectral variations of one woody species (*Maireana sedifolia*) in one day with different conditions (vigour, senescence, ungrazed and grazed) at MFC (presenting the existing variation for one object)

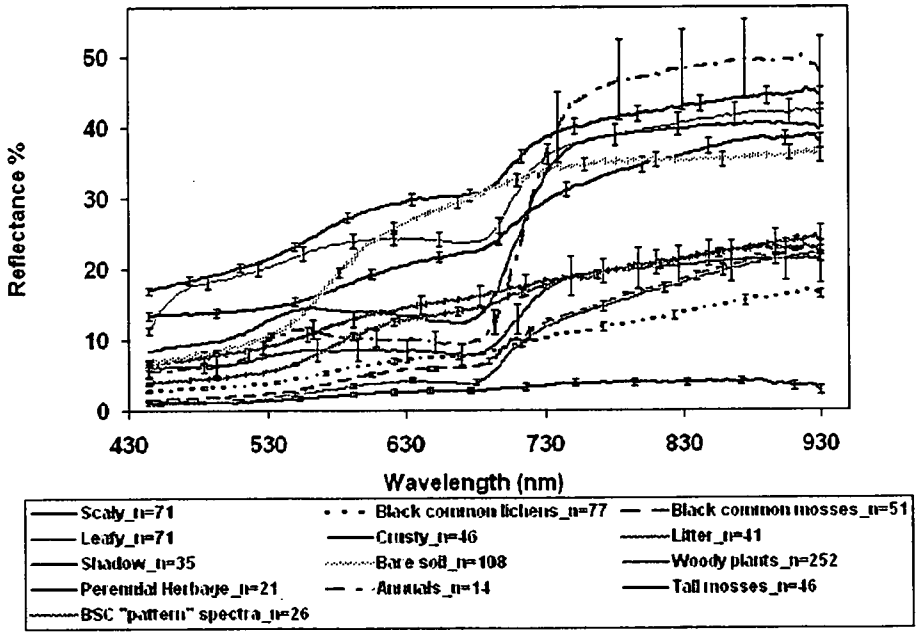

Figure 5-5. Dry spectra (mean spectral values) ± standard error (vertical bars) at MFC (presenting the existing variations and complexities for an image pixel)

5-5-1-3. Wet Spectra of All Land Covers at MFC

Wet spectra of different land covers are presented in Figure 5-6. The mixture and complexity issues of spectra in wet conditions are also similar to the dry conditions. Similarly the spectral patterns particularly at the "red edge", which are affected by chlorophyll contents of BSC growth, are considerable. Thus wet NIR region characteristics may create the possibility of discriminating different land covers from each other.

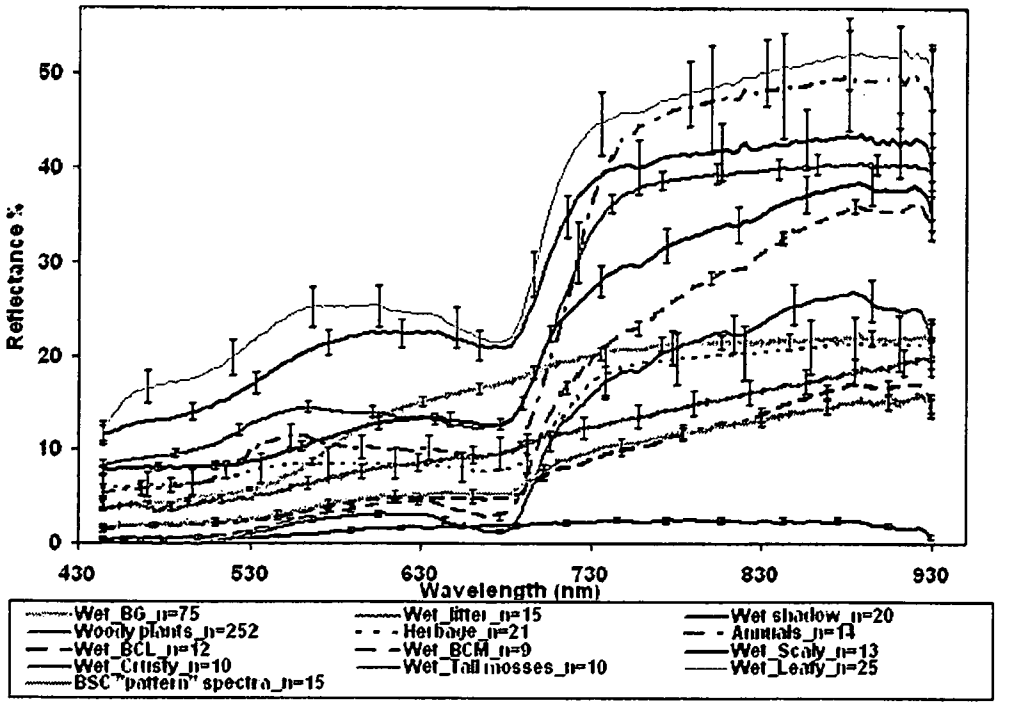

Figure 5-6. Wet spectral components (mean spectral values) ± standard error (vertical bars) at MFC (presenting the existing variations and complexities for a pixel of image)

5-5-2. Dry Spectra *vs.* Wet Spectra for Single Objects

5-5-2-1. Main Land Covers

Figure 5-7a-d shows spectral signatures for dry components are brighter than the same components when wet. Bare soil, stone and shadow have typical spectra such as those which were reported by previous studies (JPL, 2005; USGS, 2005). However, litter spectra differ slightly from those reported, especially having darker spectra from red to NIR regions. The shadow spectrum, as would be expected, has a darker signature than other land covers. However, the reflectance of shadow is related to the density of canopy cover. For example, there are very large spectral variations under *Acacia* spp., in comparison with the collected spectra from under *Maireana* spp. with high-density of canopy cover. The data presented are representative of the high-density canopy cover of plants such as *Maireana* spp. Vascular plant spectra for dry and wet conditions for all analyses were assumed to be the same, and their spectral properties are presented in Figure 5-7e for three main woody, perennial herbage and annual plants. The woody plants were brighter than the herbage in the visible but darker than the annuals in NIR wavelength. This happened because of the percentage of the woody materials in comparison with the green parts of these plants and absorption of light in different wavelength regions.

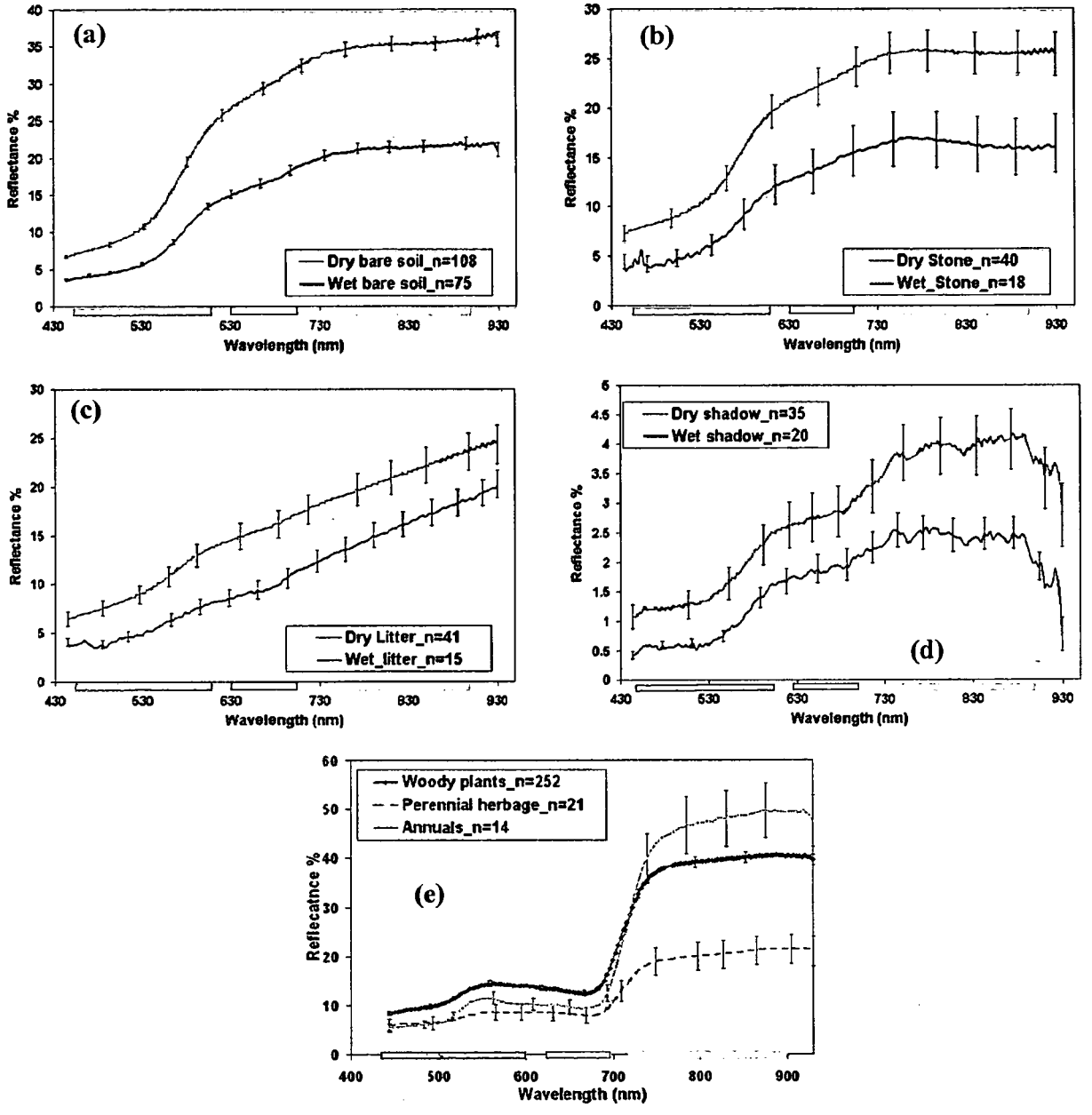

Figure 5-7. Mean dry *vs.* wet spectra for main rangeland covers ± standard error (vertical bars): a) bare soil; b) stone; c) litter; d) shadow, and e) vascular plants (the same data for dry and wet conditions) at MFC (Four bands of TM are shown with different colours)

However, the mean perennial herbage spectra show distinct reduction in brightness of the NIR region and darker spectral value in the visible region but are not clearly distinguishable. Overall, woody plants have the highest spectral variation between vascular plants, with very close spectra to the litter for senescence and highly grazed *Maireana* spp. This is because of the reduction of green

components in these plants. The annual plant spectra were the most variable, ranging from forbs to grasses, with the result that their mean spectra had higher error levels than the other plants.

5-5-2-2. BSC Groups

Figure 5-8a-g shows that wet BSC in comparison with dry conditions generally exhibit sharp "red edge", which are the consequence of chlorophyll increase. The spectral value for the main BSC groups (BCL and BCM with 82%) had similar reflectance in the visible region but differed in albedo in the NIR. Three groups including Leafy, Scaly and Crusty Lichens with 17% cover, displayed different reflectance patterns, that is, higher in the blue, green, red and NIR than the other BSC groups, which are the consequence of bright pigments in the thallus of these groups. Spectral values in the blue, green and red bands of TM imagery for most of the BSC groups when dry are brighter than in the wet conditions, except with mixed patterns for Leafy Lichens. On the other hand, NIR band has mixed patterns for different BSC groups. There are distinguishable, brighter spectral values of NIR in BCM, Leafy Lichens and Tall Mosses, whereas, it is very close and mixed for BCL, Crusty, and Scaly Lichens. As can be seen from Figures 5-8g and h, spectra of "BSC pattern spectra" (5-4-4) for dry and wet conditions are affected by background soil and they have similar spectral pattern to the bare soil spectra, but it is slightly different in the wet conditions because of the moisture effects on soil and BSC.

5-5-3. Spectral Characteristics of the Main BSC Groups and Other Land Covers

5-5-3-1. Discrimination between Dry BSC Groups

The dry spectra of the six BSC groups are plotted versus the dry land covers in each graph to visually compare the similarities and differences of each group with the selected rangeland features. By considering these plots, two main super-groups initially can be identified among the six groups (Figure 5-9a-h). The first super-group includes: BCL, BCM and Tall Mosses with 82.68% cover, and the second super-group Leafy, Scaly and Crusty Lichens with 17.04% cover.

5-5-3-2. Discrimination between the Dry BSC Groups and Other Dry Land Covers

Figure 5-9a shows bare soil spectra, particularly in the green, red and NIR bands are very close to the spectra of Leafy, Scaly and Crusty Lichens with 17.04% cover. It seems BSC with bright pigments have similar spectral patterns, particularly in the visible region, with bare soil at MFC.

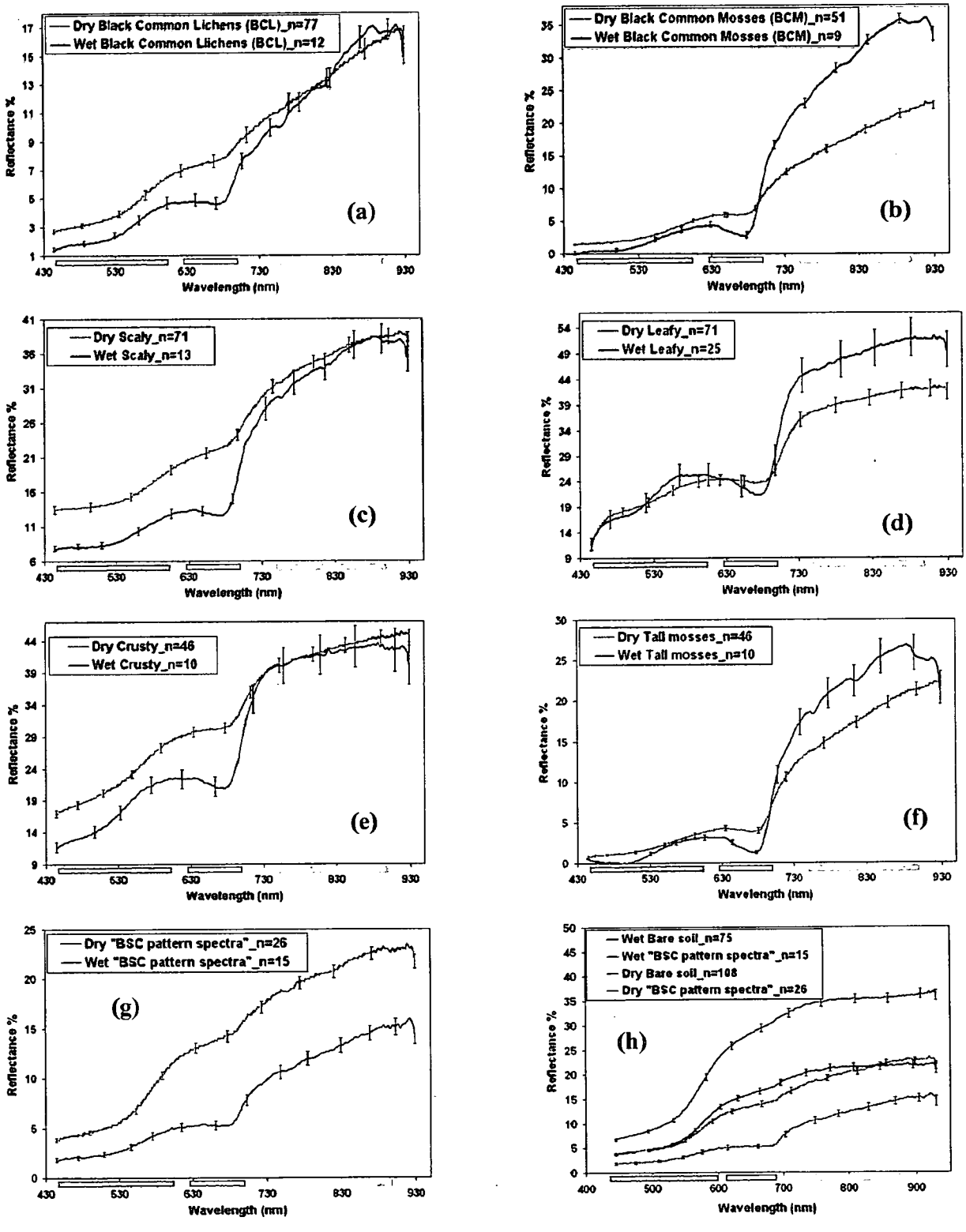

Figure 5-8. Dry *vs.* wet spectra for BSC groups and BSC patterns, ± standard error (vertical bars): a) Black Common Lichens (BCL); b) Black Common Mosses (BCM); c) Scaly Lichens; d) Leafy Lichens; e) Crusty Lichens; f) Tall Mosses; g) "BSC patterns spectra", and h) bare soil versus "BSC pattern spectra" at MFC (Four bands of TM are shown with different colours)

On the other hand, distinguishable differences exist between bare soil spectra and the other 82.68% of BSC cover such as BCL, BCM and Tall Mosses, which are the results of dark-colour pigments of these groups and bright colour of soil at MFC. The spectral signature of stone is also close in value in red and green bands with Leafy, Scaly and Crusty Lichens, but there are identifiable differences with the mentioned BCL, BCM and Tall Mosses cover. Litter has visually different spectral patterns from all BSC groups, which means live photosynthetic and non-living photosynthetic components have different characteristics in absorption and reflection of light. Shadow spectra have different patterns to Leafy, Scaly and Crusty lichens cover in various bands, however, they are very close in bands 1, 2 and 3 to BCL, BCM and Tall Mosses, which means the effect of dark-colour pigments in the visible region are the same as broken light reflectance under the shadow of dense plants and possibly creates a source of error in the remote sensing of BSC.

Woody plants have distinguishable spectral patterns from BCL, BCM and Tall Mosses. The spectral pattern of woody plants is similar in NIR, blue and green bands, but maybe the sharp "red edge" can help to discriminate them from the Scaly and Crusty Lichens. Leafy Lichens (1.90%) have the highest similarity with woody plants with which they can easily be confused. Perennial herbage spectra is very close to BCL, BCM and Tall Mosses, but slight differences in the NIR, green and blue bands would help to discriminate perennial herbage from those groups. Scaly and Crusty Lichens have different spectra from the perennial herbage, but the spectral patterns of the Leafy lichens, although they have brighter spectral value, are similar to these plants. Annual plants have similar spectral value in the NIR region with Scaly, Crusty and Leafy Lichens, and in blue and red bands with BCL, BCM and Tall Mosses. However, a distinguishable "red edge" can help to separate annuals from different BSC groups. Figure 5-9h shows dry "BSC pattern spectra" versus other land covers. As can be seen from the graph, the spectral pattern of dry "BSC pattern spectra" is similar to the litter and bare soil, but the brightness value is brighter in comparison with bare soil. The spectral value of "BSC pattern" in the blue band region is almost the same as other land covers. The spectrum of "BSC pattern" is similar in pattern and brightness value to the litter spectrum.

5-5-3-3. Discrimination between Wet BSC Groups

Figure 5-10a-h shows the six BSC groups in the wet conditions, which are plotted versus one of the other land covers in each graph to compare variations. By considering the plots' similarity to the dry conditions, two main super-groups can be also identified among the wet BSC groups. Although differences between these two super-groups are reduced in comparison with the dry conditions, there are still discernable differences.

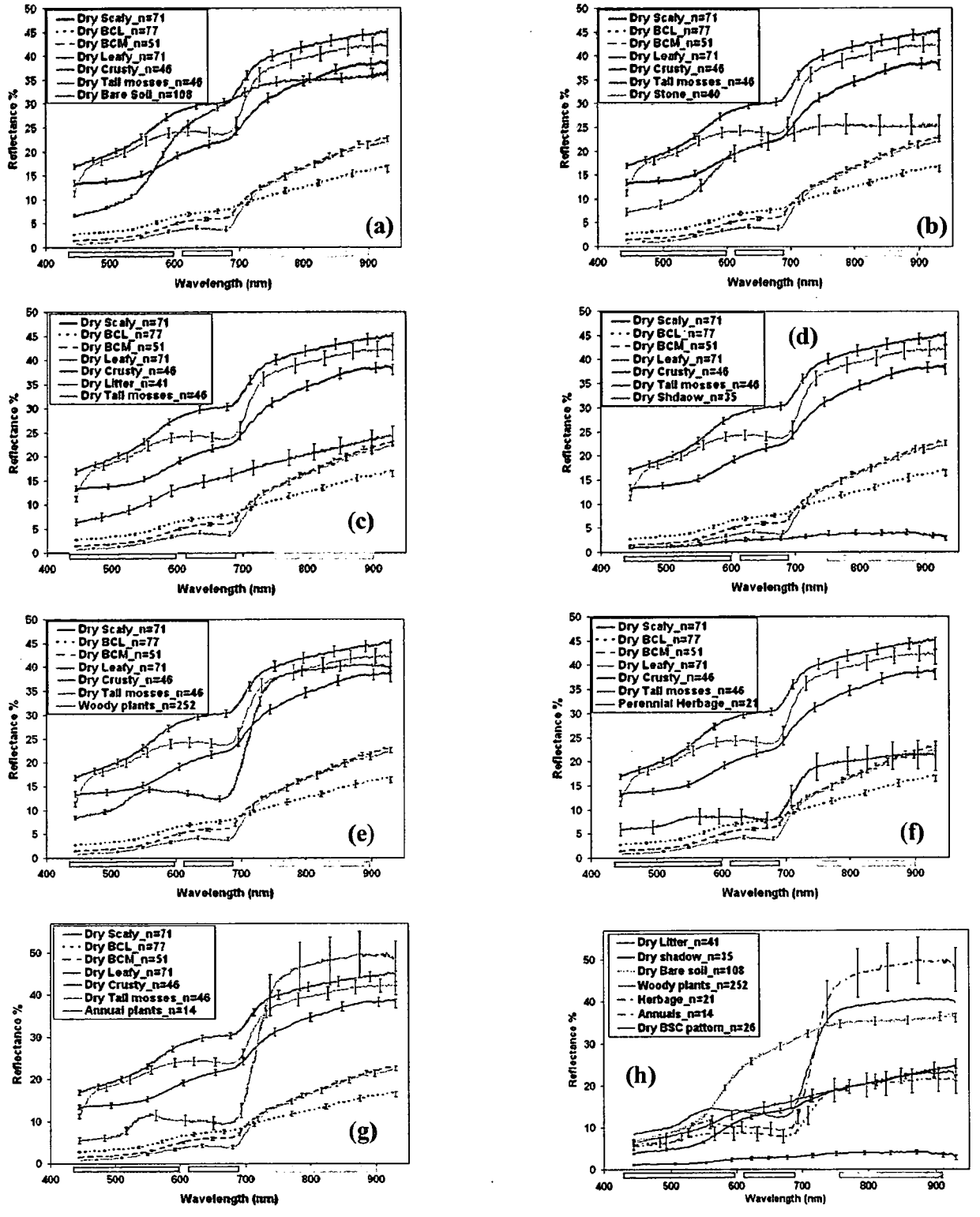

Figure 5-9. Spectral patterns (mean and standard error) of dry BSC groups *vs.* other land covers: a) bare soil *vs.* BSC groups; b) stone *vs.* BSC groups; c) litter *vs.* BSC groups; d) shadow *vs.* BSC groups; e) woody plants *vs.* BSC groups; f) perennial herbage *vs.* BSC groups; g) annuals *vs.* BSC groups, and h) "BSC pattern spectra" *vs.* other land covers at MFC (Four bands of TM are shown with different colours as blue, green, red and NIR)

The same as in the dry conditions, the first group includes: the BCL, BCM and Tall Moss (with 82.68% cover) whilst the second group includes Leafy, Scaly and Crusty Lichens (with 17.04% cover). There are also some variations within and between these two groups, but these variations are considered in the multispectral data space analyses in Section 5-5-4. Therefore, the best option is to use hyperspectral contexts to analyse these variations. Moreover, by considering the lack of information about the chemical characteristics of BSC groups and their possible effects on light reflectance and absorption, a chemical analysis of BSC groups would help to interpret the spectral variations from group to group and also create the possibility of the comparison with other land covers.

5-5-3-4. Discrimination between the Wet BSC Groups and Other Wet Land Covers

Figure 5-10a shows the spectrum of bare soil, which has some similarities with various BSC groups, however, the overall pattern is different from BSC groups. Stones (Figure 5-10b) have similar spectra to bare soil in the wet conditions with some similarities in certain bands of TM imagery with some BSC groups, but both stone and soil can be differentiated from all BSC groups. Litter (Figure 5-10c) has the highest similarity with BSC groups including BCL, BCM, Scaly Lichens and Tall Mosses (with 94.98% cover) in the blue, green, and red regions and in band 4 of TM imagery with BCL (with 62.05% cover). Shadow data (Figure 5-10d) can be differentiated from the Scaly, Crusty and Leafy Lichens in different bands, however, its spectral value is very close to BCL, BCM and Tall Mosses (with 82.68% of BSC cover) in TM bands 1, 2 and 3. Woody plants have a similar spectrum to some of the BSC groups such as Scaly and Leafy Lichens, BCM and Tall Mosses. Overall, the closest value of different bands of woody plants is similar to the Scaly Lichens with 12.30%. The spectral plot of herbage (Figure 5-10f) has a different pattern from the BSC groups but, in certain bands, they have some similarities or close spectral value with different groups. Annual plants have similar spectral patterns to Leafy, Scaly and Crusty Lichens, and mosses, but the spectral value at least in one band is distinguishable. Figure 5-10h shows wet "BSC pattern spectra" versus other land covers. Wet "BSC pattern" have lower brightness value than most of the other land covers. However, the spectral pattern of wet "BSC pattern spectra" is similar to perennial herbage plants. There is high similarity between the brightness value of litter and "BSC pattern spectra". Overall, by considering the lack of information about the chlorophyll contexts of different BSC groups in the active or growth stage to use in the interpretation of spectral signatures, an examination of chlorophyll contexts of different BSC groups would be valuable in the interpretation and characterization of BSC spectra.

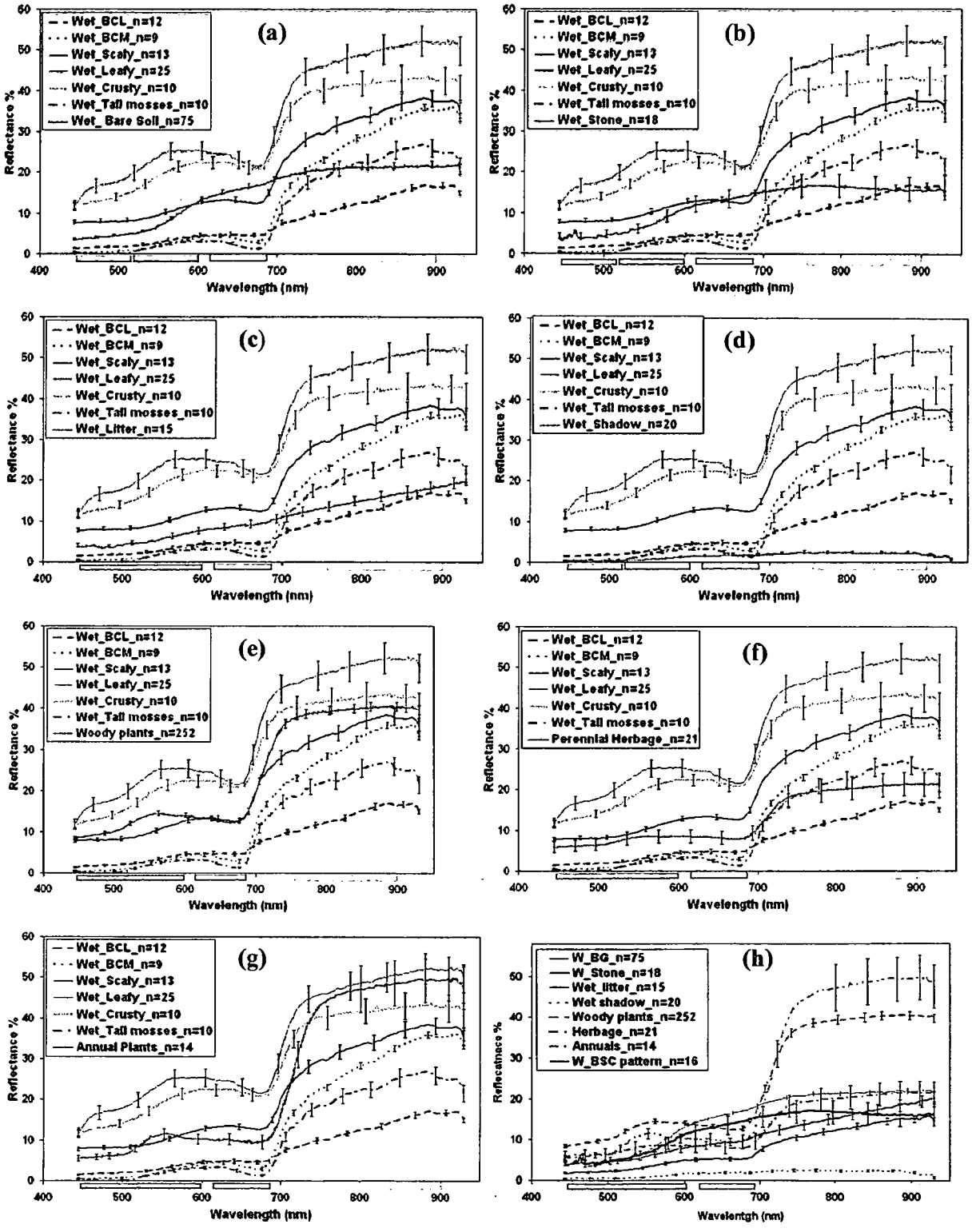

Figure 5-10. Mean spectral plots of wet BSC groups *vs.* other land covers ± standard error (vertical bars): a) bare soil *vs.* BSC groups; b) stone *vs.* BSC groups; c) litter *vs.* BSC groups; d) shadow *vs.* BSC groups; e) woody plants *vs.* BSC groups; f) perennial herbage *vs.* BSC groups; g) annuals *vs.* BSC groups, and h) BSC pattern *vs.* other land covers at MFC (Four bands of TM are shown with different colours as blue, green, red and NIR)

5-5-4. Land Covers in the TM Data Space

Different bands of synthesized TM imagery were investigated to find the best discernable pattern of different land covers on the Cartesian data space. By investigating different bands, this chapter concluded that band 3 versus band 2 had the best discernable pattern for all land covers. Therefore, these bands were selected to test the effects of BSC or the possibility of detecting these components with the soil line-based indices such as the PD54 (2-10-3). This section was conducted with the concept of possible perpendicular distance value (2-10-3) increase (or any effects) in dry or wet conditions by the change of soil or vegetation lines (see glossary for soil and vegetation lines & 2-10-3) by the effects of BSC groups.

5-5-4-1. Dry Conditions

Figure 5-11 presents the simulated data space of TM band 3 versus band 2 for major land covers in dry conditions. There is little overlap between BSC and bare soil or stone spectra, but considerable overlap with perennial plants' (woody + herbage) spectra. An important finding from this graph is that BSC do not affect the position and orientation of the soil line. This is particularly important from the PD54 perspective, which is based on the soil and vegetation lines. The second important point that can be concluded from this graph is that almost all of the 386 BSC spectral samples are plotted between the soil and vegetation lines. The PD54 uses the perpendicular distance between these two lines as the basis for image interpretation. More importantly, two main super-groups of BSC including BCL and BCM (with 82.23% cover) have data space close to the soil data, which suggests that they do not affect the vegetation or soil lines. Mixed patterns exist among the litter, shadow and BSC group data. Overall, BSC groups in dry conditions do not effect the vegetation and soil lines, therefore soil line-based indices such as the PD54 are not a suitable index on the area in which BSC are common if image(s) is/are selected in the dry state of BSC.

Spectral Characteristics of BSC Groups *vs.* Other Land Covers in Dry Conditions

Figure 5-12a-g shows BSC groups versus other land covers when all samples except vascular plants were in the dry conditions. Figure 5-12a shows BCL do not overlap with bare soil. Although BCL overlap with vascular plants, distinct distance exists between the vegetation line and their spectra. BCL also overlap with litter and shadow data. The second major BSC group is BCM. It exhibits a distinct pattern from bare soil and does not affect the soil line (Figure 5-12b).

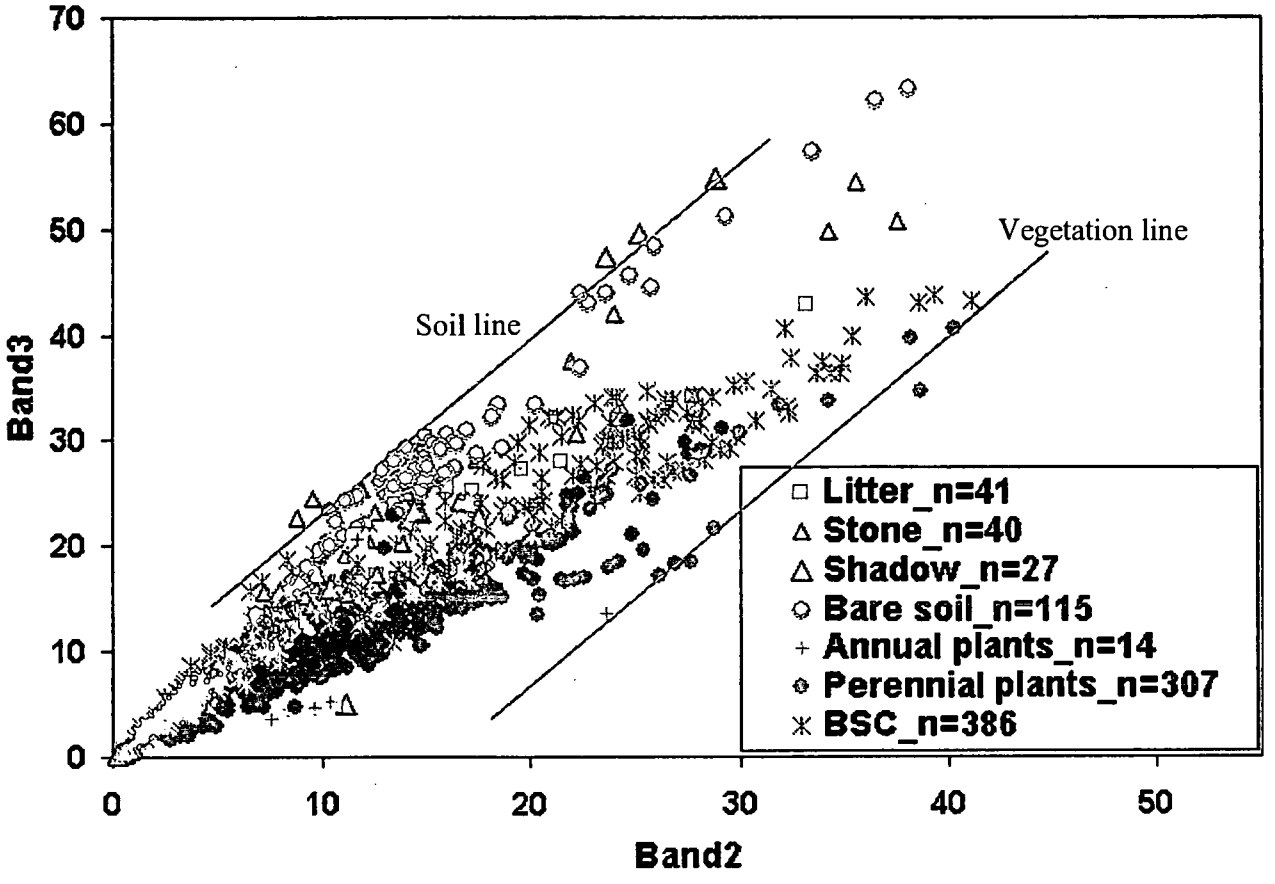

Figure 5-11. Distribution of ground-level reflectance data for bare ground, litter, stone, shadow, perennials (woody + herbage), annuals and BSC in simulated TM data space for bands 32 (equals to the bands 54 in MSS data space)

It has overlap with vascular plants, but distinct distance from the vegetation line. It has strong overlap with shadow, litter and stone data. Scaly Lichens have very little overlap with soil spectra, but a distinct pattern from the soil line (Figure 5-12c). Scaly Lichens also overlap with vascular plant spectra, but have a distinct pattern from the vegetation line. Scaly Lichens overlap with stone, and particularly with litter data. This group has no overlap with shadow data. Leafy Lichens (Figure 5-12d) have no overlap with soil data, but very high overlap with vascular plants spectra. Distinct distance exists between the vegetation line and the pattern of Leafy Lichens, but it seems that this is the only BSC group that may effect the vegetation line. They have no overlap with shadow data, and little overlap with stone and litter data. Crusty Lichens (Figure 5-12e) have distinct patterns from soil with no effect on the soil line, but strong overlap with vascular plants. In spite of this overlapping, there is a distinct distance between the vegetation line and Crusty Lichens. They have no overlap with shadow data, but a small overlap with stone and litter data.

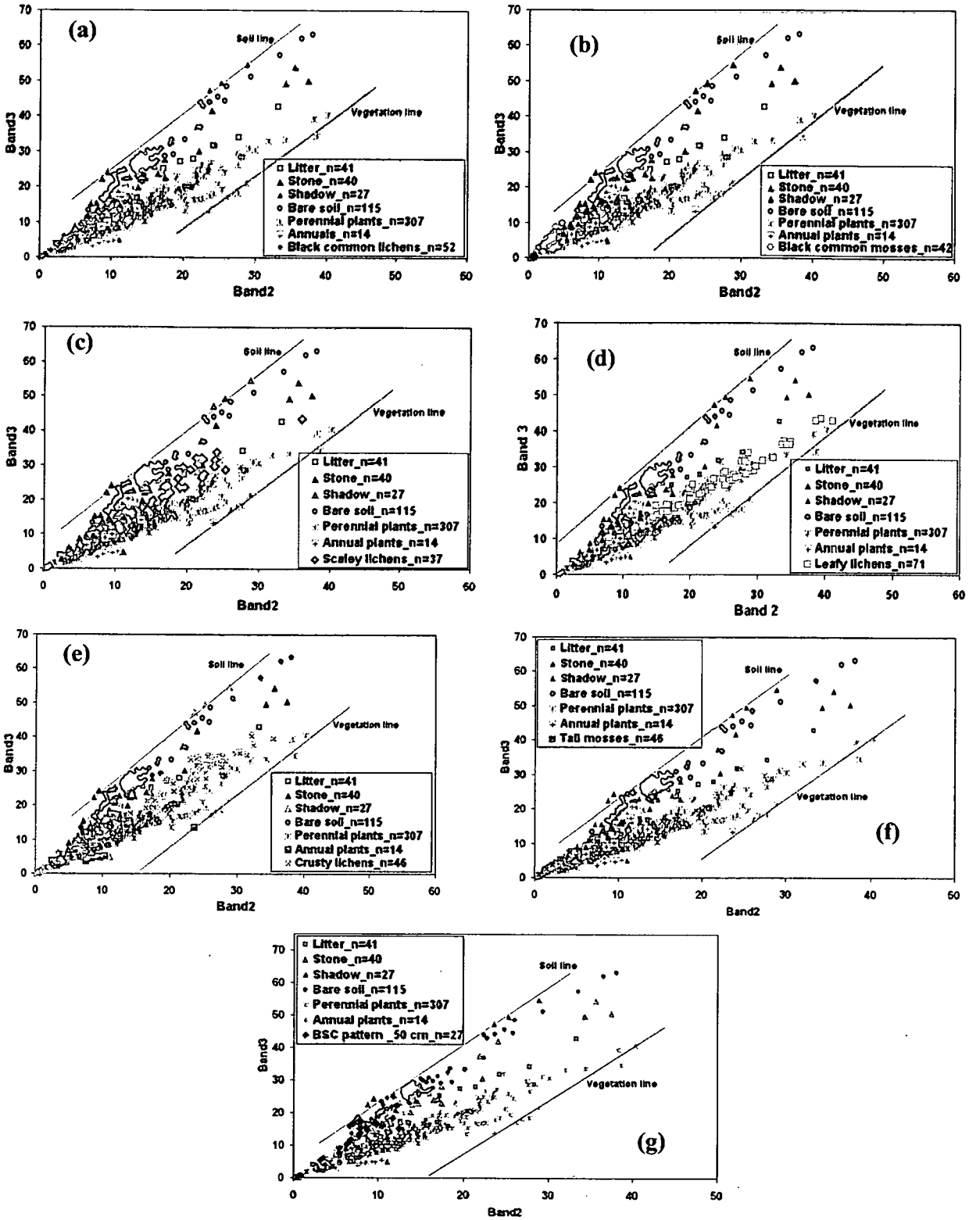

Figure 5-12. Distribution of ground-level reflectance data for bare ground, litter, stone, shadow, perennials (woody + herbage), annuals with dry: a) Black Common Lichens; b) Black Common Mosses; c) Scaly lichens; d) Leafy Lichens; e) Crusty Lichens; f) Tall Mosses, and BSC pattern spectra in the TM data space for bands 3 *vs.* 2 to conceptualize the PD54 for BSC detection by considering BSC groups in dry conditions at MFC

Tall Mosses (Figure 5-12f) have a distinct pattern from the soil spectra and no effect on the soil line. They overlap with vascular plants' spectra, but have no effect on the vegetation line. Tall Mosses have very high overlap with shadow and litter data but very low overlap with stone data. Finally, "BSC pattern spectra" (Figure 5-12g) show mixed results but with data close to the soil spectra rather than the BSC spectra. It means that soil background affected the spectral data, and "BSC pattern spectra" are more similar to the bare soil, BCL and mosses. By considering the BSC groups and "BSC pattern spectra", they do not effect the soil or vegetation lines in dry conditions, thus soil line-based indices such as the PD54 are not a sensitive index in the area in which BSC are common.

5-5-4-2. Wet Conditions

Figure 5-13 shows the data space of band 3 versus band 2 of TM imagery for major land covers with BSC in wet conditions. As in dry conditions, little overlap exists between BSC, bare soil and stone spectra, but there is very large overlap with perennial plants, shadow and litter spectra. In wet conditions BSC also do not effect the soil and vegetation lines. However, in comparison with dry conditions the values of the wet spectra are larger and closer to the vegetation line. Two important groups of BSC including BCL and BCM (with 82.23% cover) have data space between the soil and vegetation lines. The same as dry conditions, there are no distinguishable patterns between BSC and litter or shadow data, particularly with BCL and BCM. Annuals are much closer to the wet BSC in comparison to dry conditions. Overall, in wet conditions soil and vegetation lines is defined by bare soil and vascular plants, thus indices such as the PD54 are not an appropriate index to use in the area in which BSC are common even in the wet conditions.

Spectral Characteristics of BSC Groups vs. Other Land Covers in Wet Conditions

Figure 5-14a shows wet BCL versus other land covers. BCL has close spectra to the wet bare soil but the overlap is very low, and it does not effect the soil line. BCL has overlap with vascular plants; but, there is distinct distance between the vegetation line and BCL patterns. It has overlap with litter and shadow data, but no overlap with stone data. BCM has a distinct pattern from bare soil and does not effect the wet soil line (Figure 5-14b). It overlaps with vascular plants, but has distinct distance from the vegetation line. It is mostly overlapped with shadow and litter data, but has little overlap with stone samples. The third group is Scaly Lichens with 12.30% cover. It has little overlap with soil spectra, but a distinct pattern from the wet soil line (Figure 5-14c). It overlaps with vascular plants, but also has a distinct pattern from the vegetation line. It overlaps with stone, and particularly with litter data.

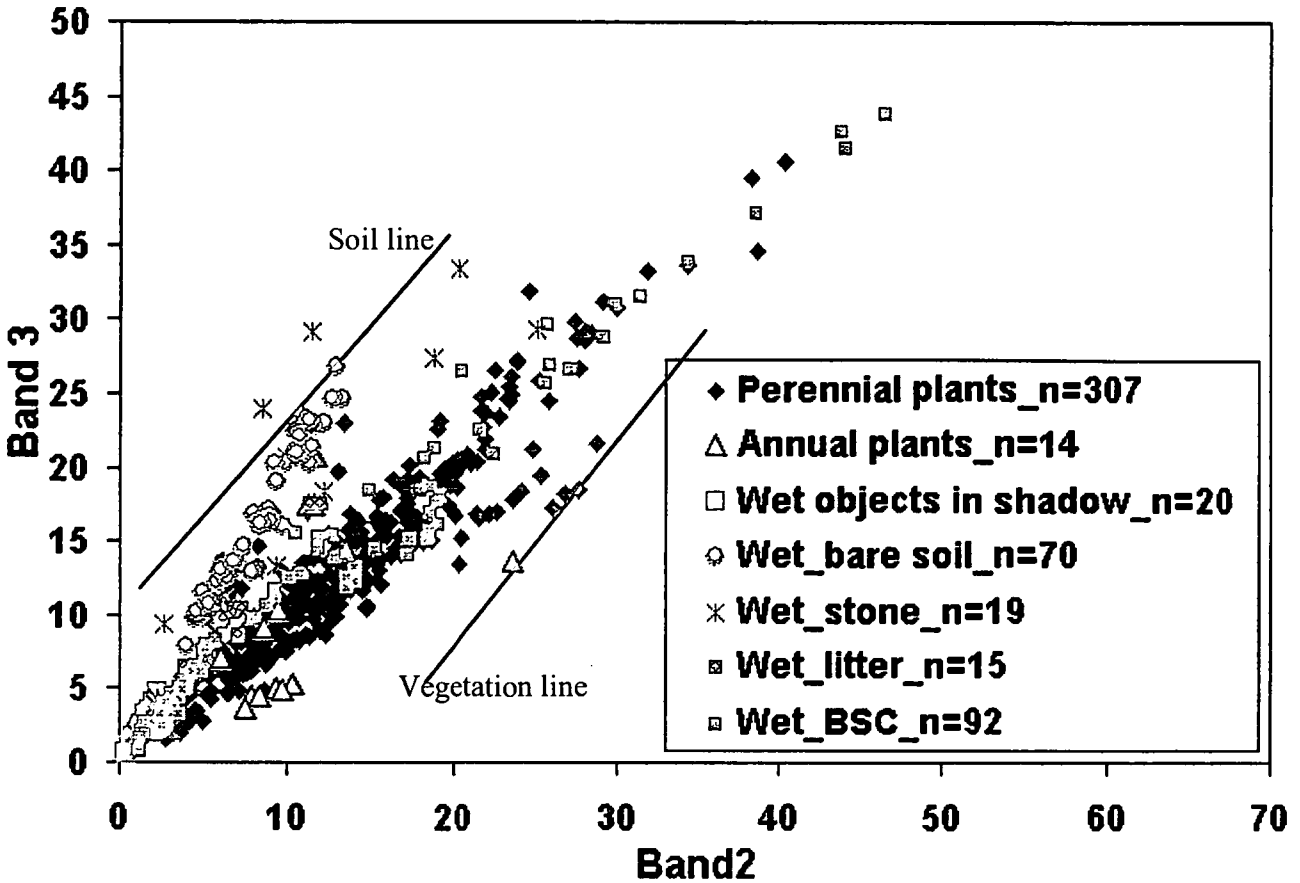

Figure 5-13. Distribution of ground-level reflectances for wet bare ground, litter, stone, and wet objects in shadow, perennials (woody + herbage), annuals with wet BSC groups in the TM data space for bands 3 *vs.* 2 to conceptualize the PD54 for BSC detection in wet conditions at MFC

This group has no overlap with shadow data. Leafy Lichens (Figure 5-14d), have no overlap with soil samples, but very large overlap with vascular plant data. There is a distinct distance between the vegetation line and the pattern of this group, but it seems that in wet conditions, the only BSC group that may effect the vegetation line is this group. They do not overlap with shadow, stone or litter data. Crusty Lichens (Figure 5-14e) have a distinct pattern from soil, stone, litter and shadow data, but the largest overlap with vascular plants. In spite of this overlapping, distinct distance exists from the vegetation line, and it seems that in certain situations it may effect the vegetation line. Further data is required to conclude the real extent of the effects of Crusty Lichen on the vegetation line. They have no overlap with shadow, litter and stone data. Tall Mosses (Figure 5-14f) have a distinct pattern from the soil data and no effects on the soil line. They overlap with vascular plants, but have no effects on the vegetation line. Tall Mosses have very high overlap with shadow and a small overlap with litter, but have no overlap with stone data.

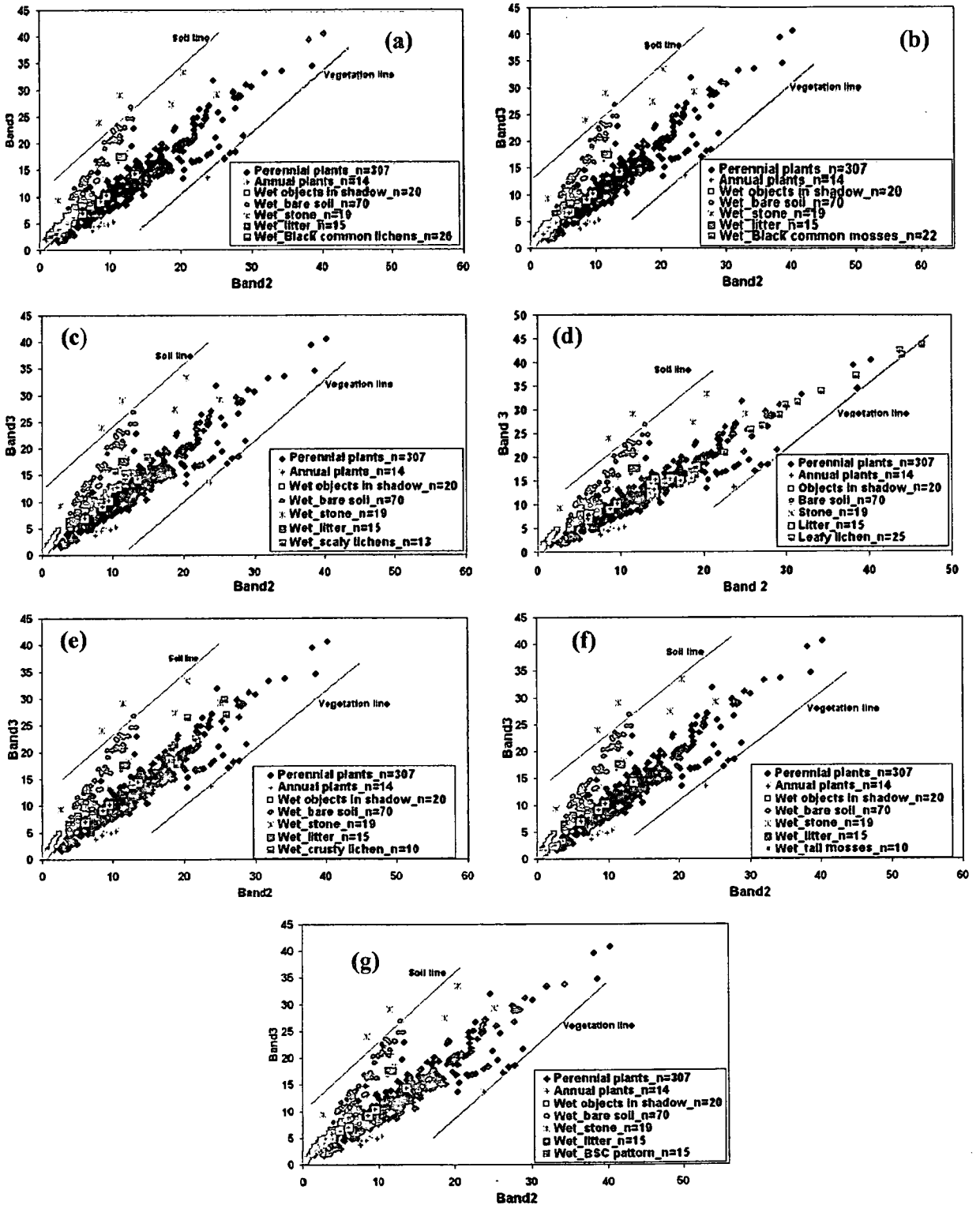

Figure 5-14. Distribution of ground-level reflectances for wet bare ground, litter, stone, and wet objects in shadow, perennials (woody and herbage), annuals with wet: a) Black Common Lichens; b) Black Common Mosses; c) Scaly Lichens; d) Leafy Lichens; e) Crusty Lichens; f) Tall Mosses, and BSC patterns in the TM data space for bands 3 *vs.* 2 (equals to the bands 54 in MSS data space) to conceptualize the PD54 for the effect of BSC groups in wet conditions at MFC

Finally, "BSC pattern spectra" (Figure 5-14g) shows different results from the dry conditions. In the wet conditions, almost all spectra shift considerably away from the soil data and soil line toward the vegetation data. Soil background has very low affect on the spectral value of mixed soil and BSC patterns. This is important, particularly for bare pixel selection for the soil line in dry and wet conditions. Overall, individual BSC groups and "BSC pattern spectra" emphasized that the PD54 is not a sensitive index to use in the area in which BSC occur even in wet conditions.

5-5-5. Spectral Comparison between Dry and Wet Non-living Soil Covers in the TM Data Space of Band 3 *vs.* Band 2

Figure 5-15a-d shows band 3 versus band 2 of TM imagery for dry and wet spectra of main land covers. It was conducted mostly for examining the spectral differences between dry and wet conditions, with the concept of whether if an image is selected in wet conditions there could be change for a soil line-based index such as the PD54. As can be seen from Figure 5-15a, the spectral values for wet bare soil, as expected, are reduced, but the important result is that the soil line is almost the same as with dry soils. From the collected data, there is no change in the soil line pattern and position, thus if an image is selected by wet soil, there is no considerable change in the value of a soil line-based indices such as the PD54. There is a small reduction of wetting on the spectral value of stone (Figure 5-15b), but the spectra cloud overlaps in dry and wet conditions. Therefore, there are no distinguishable different patterns, which could change the soil line-based indices on bands 3 *vs.* 2 of TM imagery. Figure 5-15c demonstrates litter spectra in wet and dry conditions and shows no discernable difference. Shadow data shows a small increase from the dry to wet spectral value (Figure 5-15d). By considering litter and shadow data there is no considerable change in the pattern and position of the cloud of spectra, which can change the soil or vegetation lines from dry to wet conditions (for comparison the scale of the graphs should be considered).

5-5-5-1. Comparison of BSC Groups with Bare Soil in Dry vs. Wet Conditions

Figure 5-16a- f, presents the bi-spectral plots for BSC groups and bare soils in dry versus wet conditions. Although the number of samples in the dry conditions is larger than in the wet conditions for BCL, the species for both conditions are the same. Dry BCL have very high spectral variation in comparison with wet. There is a distinct difference between dry soil and dry BCL. However, there is closer overlap between wet soil and wet BCL. There is a very distinct break in the spectral pattern between dry soil and dry BCM (Figure 5-16b). Although the number of spectra in dry conditions is almost doubled, overall, it seems that there is more spectral variation.

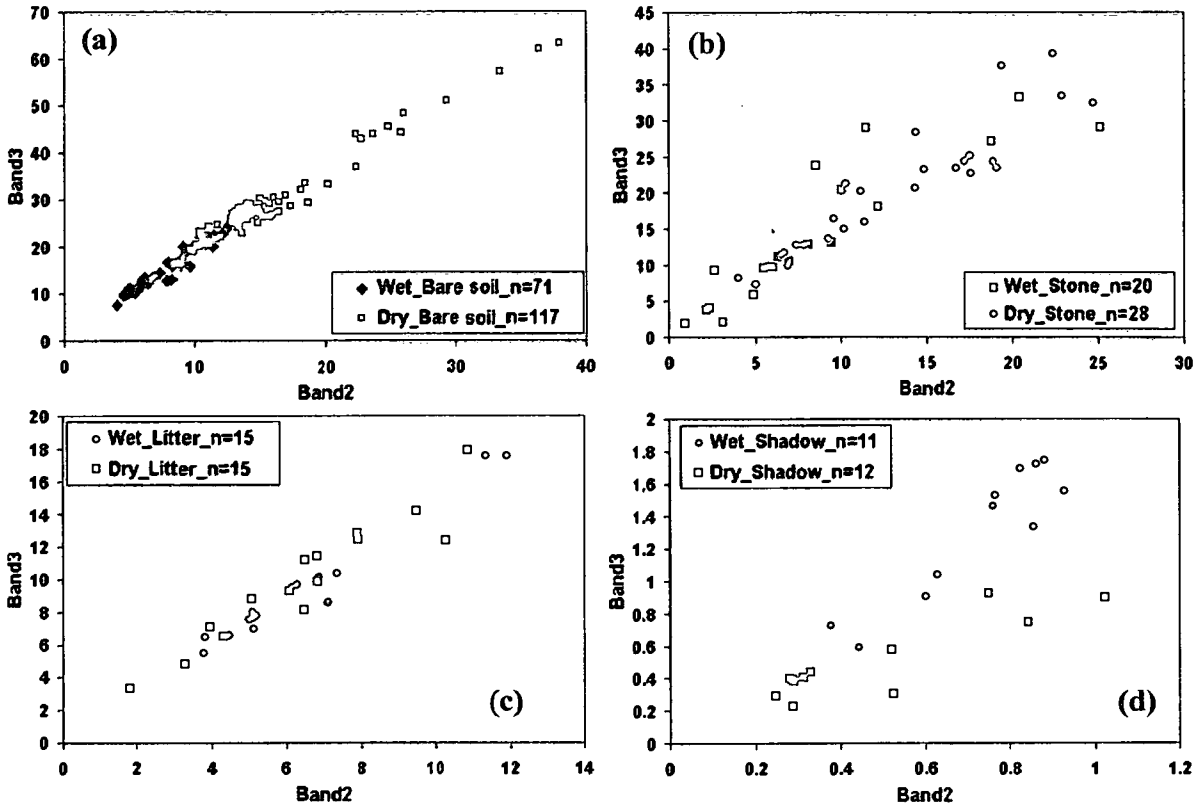

Figure 5-15. Distribution of ground-level reflectance data for dry and wet spectra for a) bare soil; b) stone; c) litter, and d) shadow at MFC

On the other hand, there is closer overlap between wet bare soil and wet BCM. Scaly Lichens (Figure 5-16c) exhibit a large spectral variation in dry conditions in comparison with wet. There is an overlapping pattern between dry soil and dry Scaly Lichens, but in wet conditions although the clouds of data are very close, there is a distinct boundary between them. Wet Scaly Lichens have a distinguishable pattern from that of dry bare soil. Leafy Lichens (Figure 5-16d), Crusty Lichens (Figure 5-16e) and Tall Mosses (Figure 5-16f) also exhibit a large spectral variation in dry conditions compared with wet conditions. In the plotted spectra there are few outlier data for black components which may relate to misclassification of BSC species on a defined group. Leafy and Crusty Lichens have distinct data clouds from bare soil in both dry and wet conditions (Figures 5-16d & 5-16e). Finally, Tall Mosses have distinct clouds of data both dry and wet with bare soil, in both dry and wet conditions (Figure 5-16f). Overall, soil line-based indices such as the PD54 are not a sensitive index on the area in which BSC occur, and vegetation and soil lines are defined by bare soil and vascular plants. Moreover, if an image is selected on dry soil and wet BSC or vice versa, there are no considerable effects of BSC groups in dry and wet conditions of soil line. See Chapter 6, Model 5, if an image is selected in dry soil and wet BSC conditions.

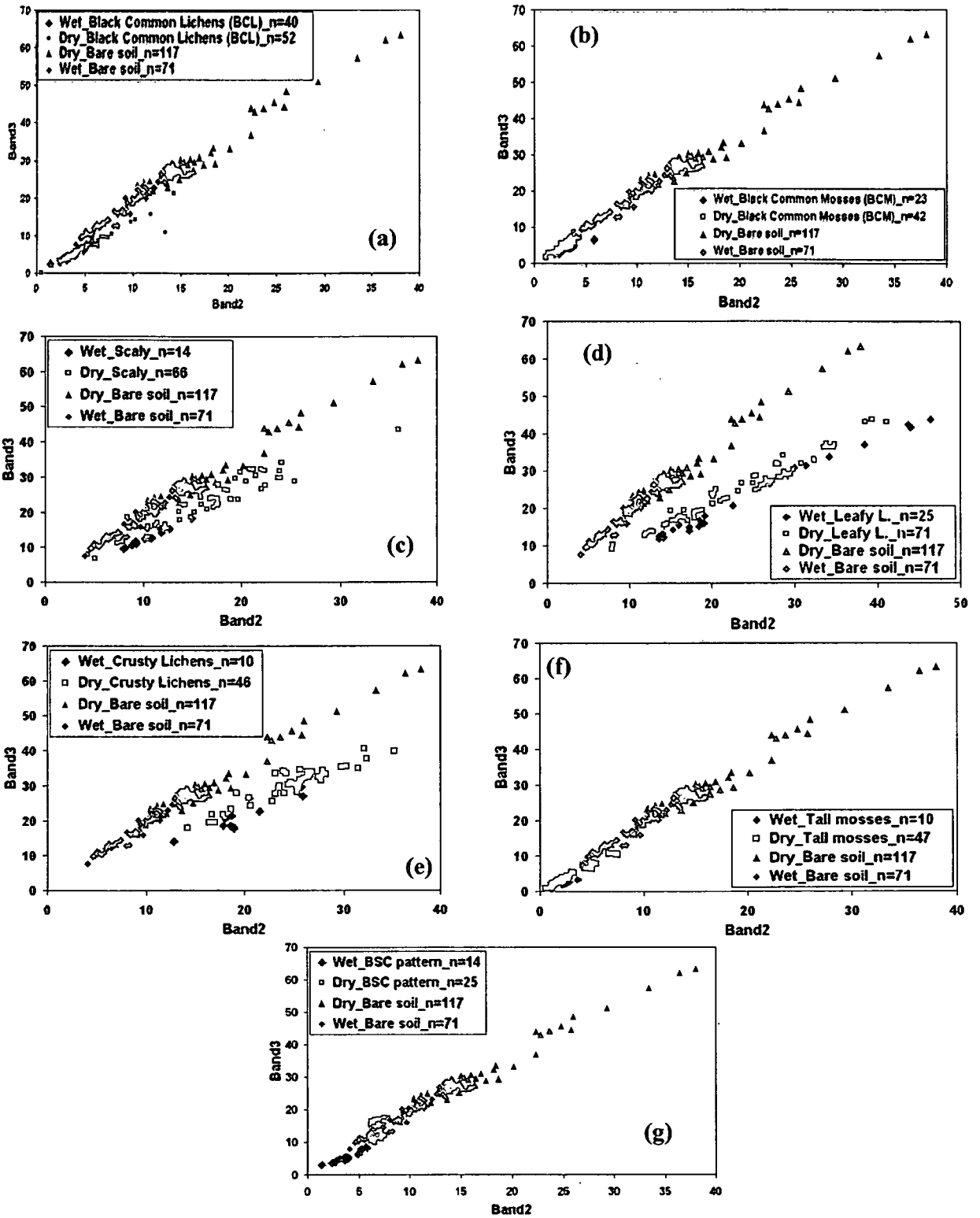

Figure 5-16. Distribution of ground-level reflectance data for dry *vs.* wet spectra: a) Black Common Lichens (BCL) *vs.* bare soil; b) Black Common Mosses (BCM) *vs.* bare soil; c) Scaly Lichens *vs.* bare soil; d) Leafy Lichens *vs.* bare soil; e) Crusty Lichens *vs.* bare soil; f) Tall Mosses *vs.* bare soil, and g) "BSC pattern spectra" *vs.* bare soil at MFC

5-5-6. Land Covers in the TM Data Space for Dry and Wet Conditions with Band Combinations of the SSI

5-5-6-1. Dry Data

Figure 5-17a-f shows the data space for TM band combinations of the SSI. Mosses have distinct data cloud patterns from other BSC groups and land covers (Figures 5-17b & f). Almost all BSC groups have distinct data clouds from the bare soil. BCM, Leafy Lichens, and Tall Mosses have distinct data cloud patterns from the soil data. BCL has little overlap with litter data. Leafy Lichens have the highest overlap with perennial plants, and mosses have the lowest overlap. BCL, Scaly and Crusty Lichens overlap slightly with vascular plants. BCM, Tall Mosses, Scaly, Crusty and Leafy Lichens have no overlap with shadow, but the important group, BCL (with 62.18% cover) has a little overlap with shadow data. Finally, stone is the only land cover which has a completely distinct data pattern from the BSC groups. Using the concept of the SSI (2-10-2), particularly BCL, BCM, Scaly Lichens, Crusty Lichens and Tall Mosses values can be interpreted as stable conditions in comparison with severe erosion and extensive deposition. Only the Leafy Lichens data cloud can be interpreted as minor to extensive deposition value. An interesting result is that BSC groups do not demonstrate any equal value to the severe erosion value in the concept of the SSI.

5-5-6-2. Wet Data

Figure 5-18a-f shows the data space between band combinations of the SSI for wet conditions. Almost all BSC groups have distinct data patterns from that of the bare soil and stone data. BCM, Leafy Lichens, Tall Mosses, Scaly Lichens and Crusty Lichens are distinct from litter data. BCL has overlaps with litter. Leafy and Crusty Lichens have the highest overlap with perennial plants, and mosses the lowest. BCL and Scaly Lichens overlap slightly with vascular plants. BCM and Tall Mosses have very little overlap with perennial plants. Leafy Lichens, Tall Mosses and Crusty Lichens have no overlap with shadow data, but BCL, BCM and Scaly Lichens have overlap with shadow. Using the concept of the SSI (2-10-2), particularly BCL, BCM and Scaly Lichens data patterns can be interpreted as stable conditions in comparison with severe erosion and extensive deposition cloud pattern for bare soil and vascular plants patterns. However, Leafy Lichens, Tall Mosses and Crusty Lichens data clouds can be interpreted as minor to extensive deposition value. The same as the dry conditions, BSC components have not demonstrated any severe erosion value in the data space of the SSI.

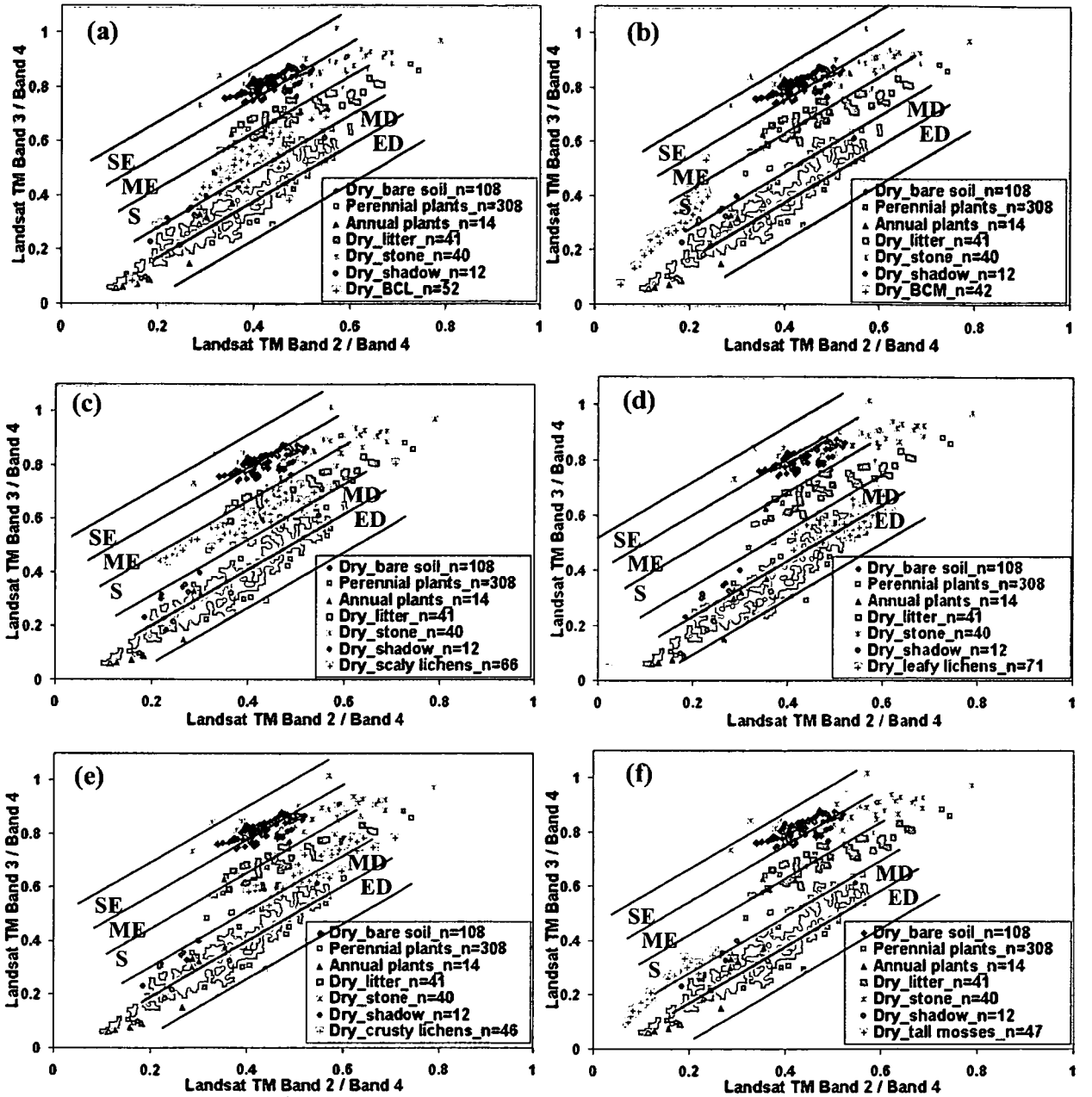

Figure 5-17. Distribution of ground-level reflectance for data space of the SSI in dry conditions: a) Black Common Lichens (BCL); b) Black Common Mosses (BCM); c) Scaly Lichens; d) Leafy Lichens; e) Crusty Lichens, and f) Tall Mosses at MFC (lines show the erosional status; SE = Severe Erosion, ME = Mild Erosion, S = Stable, MD = Minor Deposition and ED = Extensive Deposition/ see also Section. 2-10-2)

5-5-7. Land Covers in the TM Data Space for Dry and Wet Conditions with Band Combinations of the NDVI

To my knowledge, there is no evidence of using a graphical representation of numerator plotted against denominator of NDVI in recent studies. This study used collected dry and wet data to represent the fraction of band 4 ± band 3 for the NDVI in the Cartesian data space.

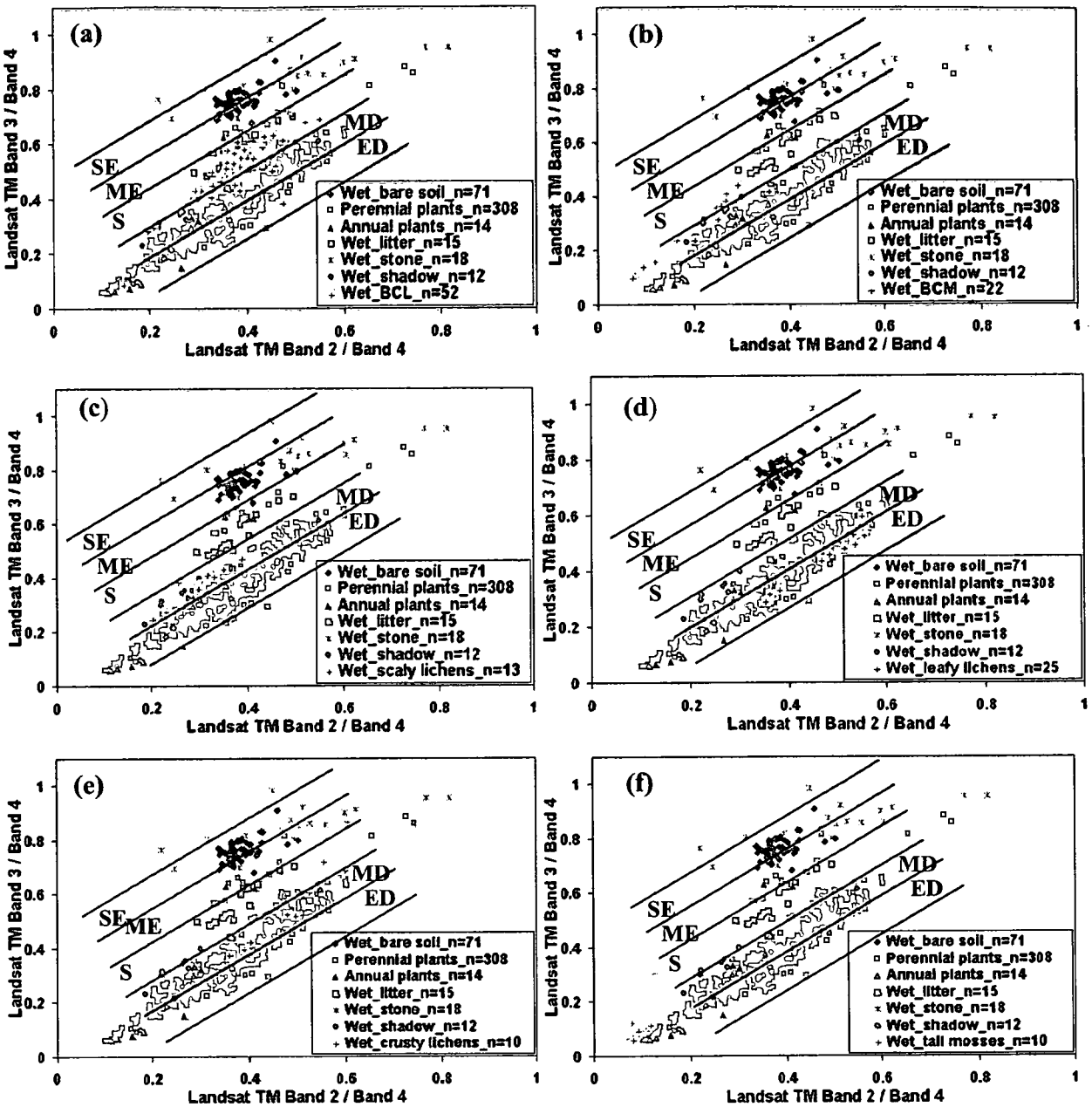

Figure 5-18. Distribution of ground-level reflectance for data space of the SSI in wet condition: a) Black Common Lichens (BCL); b) Black Common Mosses (BCM); c) Scaly Lichens; d) Leafy Lichens; e) Crusty Lichens, and f) Tall Mosses at MFC (lines show the erosional status: SE = Sever Erosion; ME = Mild Erosion; S = Stable; MD = Minor Deposition, and ED = Extensive Deposition/ see also Section 2-10-2)

5-5-7-1. Dry Data

Figure 5-19a-f presents the data space of various BSC groups for the NDVI in dry conditions. As can be seen from the graphs, mosses overlap with vascular plants and can affect the vegetation in this index. BCL, Scaly and Crusty Lichens have a little overlap with bare soil, litter and stone data, but, overall, the data pattern is somewhere between that of vascular plants and bare soil. Mosses and Leafy Lichens have no overlap with litter. BCL is the only group that overlaps shadow. Other groups are distinct from shadow.

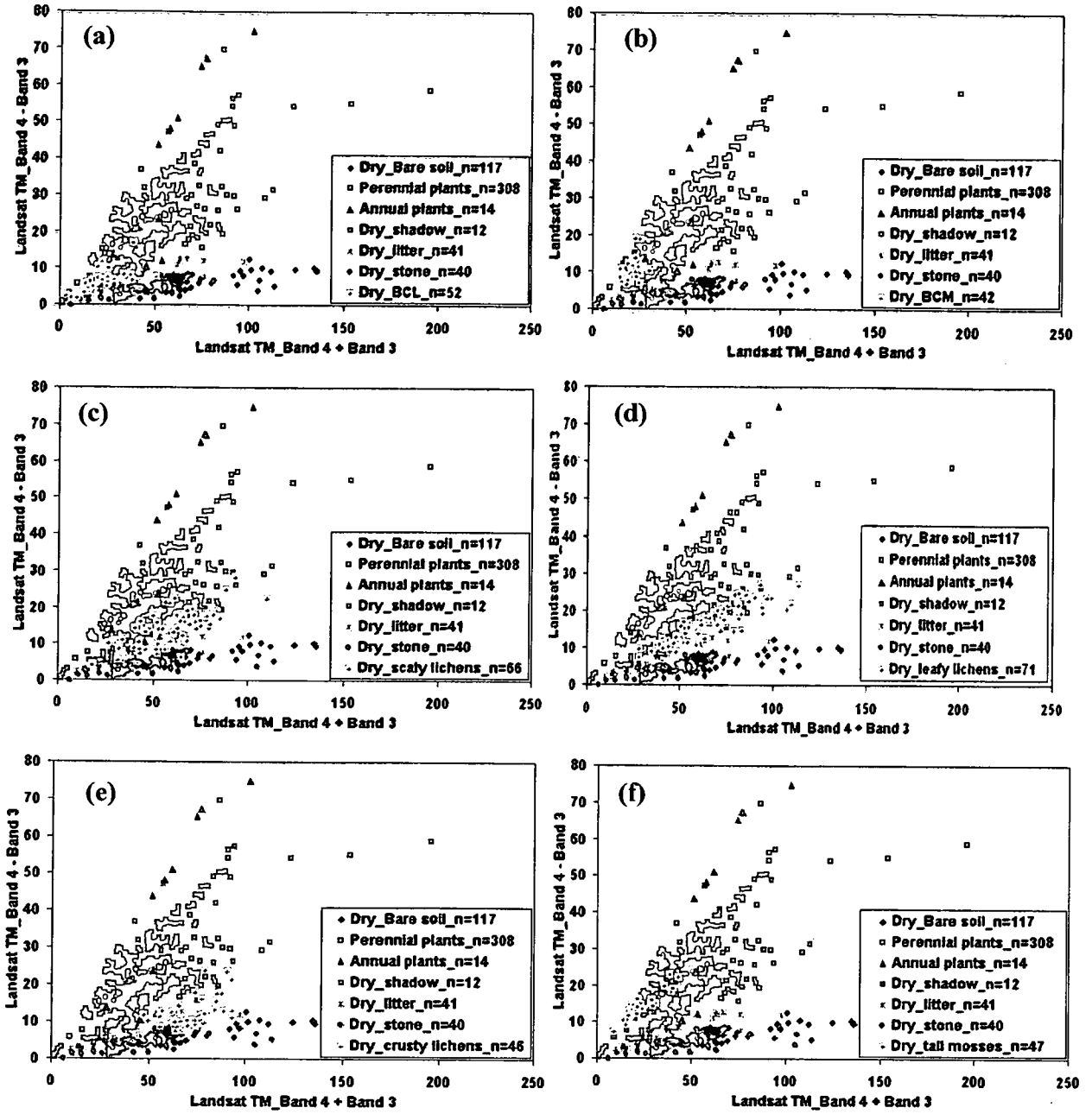

Figure 5-19. Distribution of ground-level reflectances for data space of the NDVI in dry conditions: a) Black Common Lichens (BCL); b) Black Common Mosses (BCM); c) Scaly Lichens; d) Leafy Lichens; e) Crusty Lichens, and f) Tall Mosses at MFC

5-5-7-2. Wet Data

Figure 5-20a-f presents the data space of various BSC groups for the NDVI in wet conditions. Most of the BSC groups including BCL, BCM, Crusty Lichens, Leafy Lichens and Tall Mosses have no overlap with bare soil, litter, shadow or stone. Only Crusty Lichens have a small overlap with bare soil and litter, but a distinct pattern from shadow. All BSC groups overlap with vascular plants.

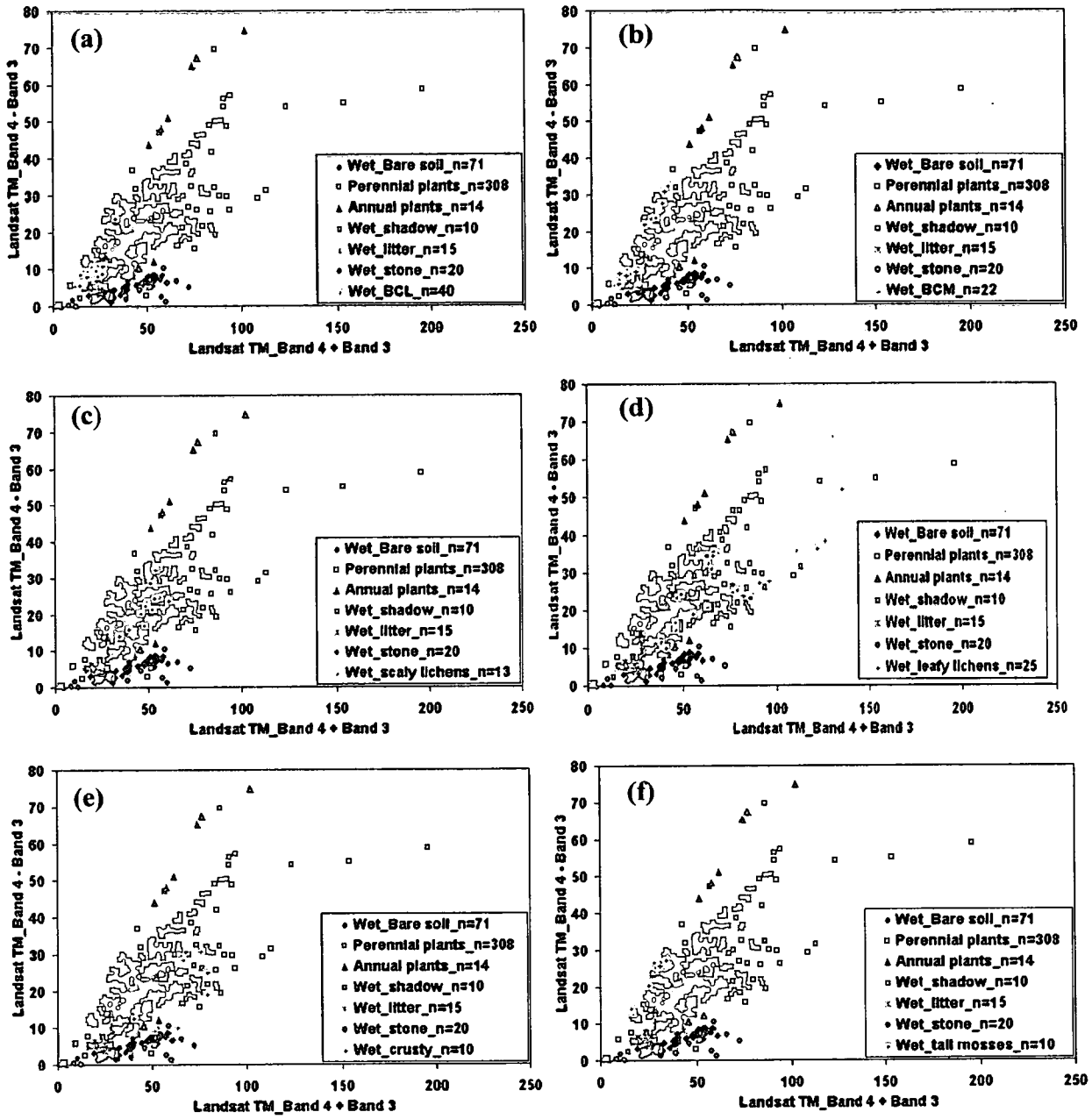

Figure 5-20. Distribution of ground-level reflectances for data space of the NDVI in wet conditions: a) Black Common Lichens (BCL); b) Black Common Mosses (BCM); c) Scaly Lichens; d) Leafy Lichens; e) Crusty Lichens, and f) Tall Mosses at MFC

5-6. Discussion

5-6-1. Spectra Characterization for the Possibility of Detecting BSC in Dry and Wet Conditions

5-6-1-1. Spectral Characteristics of BSC *vs.* Other Land Covers

The collection of spectra from 6 BSC groups and different land covers in dry and wet conditions at MFC displayed considerable variations. Some of these variations can be attributed to variation in vascular plant condition due to senescence, decline in vigour, and grazing; and some can be

attributed to differences in leaf structure, leaf to wood ratio, leaf coatings, and pigmentation in vascular and non-vascular plants. Some other variations can be attributed to soil colour and texture. Several vascular and non-vascular plants showed marked modifications in visible reflectance due to accessory pigments, notably red, pink, black and white coloration in some BSC groups, particularly in the Scaly Lichens. There were considerable variations in NIR reflectance, some of which may be caused by differences in internal leaf structure, with the semi-succulent chenopods generally displaying lower reflectance. This reduction in NIR reflectance with increased water content and reduced area of air-cell wall interface has been reported by Knipling (1970), Gausman and Allen (1973) and Lewis (2002a). Although, there were some studies for spectral analysis of cyanobateria-dominated area in the Negev desert (Karnieli *et al.*, 1996; Karnieli *et al.*, 1997; Karnieli *et al.*, 1999), there is no considerable research on lichen-dominated area, particularly in the BSC groups' level to discuss the effects of spectral variations.

There were also variations among reflectance spectra from different specimens of the same species, supporting the claim of Price (1992 and 1994), and results of this study confirmed this variations for both vascular and non- vascular plants. In the case of vascular plants, much of this variation can be attributed to differences in plant vigour; brought about by moisture stress or grazing; whereas in the case of the grasses it was due to plant vigour and senescence. In the case of BSC groups it can mostly be concluded to be from the moisture stress, colour and pigments.

Overall, thirteen (in dry and wet conditions) spectral datasets showed extreme spectral variations within and between groups, which can potentially create difficulties in the application of a remotely-sensed method for rangeland monitoring. By contrast, there are some promising patterns within the "red edge", visible and NIR brightness part of the spectrum, which can create a potential for a remotely-sensed method to detect a given component. By comparison from dry to wet conditions, brightness values, particularly in the "red edge" region have increased, which is associated with the increase of chlorophyll content in the wet conditions. Overall, two distinguishable patterns and brightness values in dry and wet conditions are: a group of spectra including BCL, BCM and Tall Mosses versus a second group including Scaly, Leafy and Crusty Lichens with brighter spectral values by comparison, and these differences can be concluded from their dark colour versus brighter colour for the second group. Apart from the magnitude of brightness, there are some differences within these two groups in both dry and wet conditions such as spectral patterns between mosses and BCL. Alternatively, despite the magnitude of brightness, there is high similarity between Crusty Lichens and BCL, giving rise to the possibility of misinterpretation. However, as Lewis (2002a) pointed out there is a requirement for more quantitative, analytical comparisons of laboratory and field spectra of land covers to

determine the extent to which they differ, and hence might be discriminated, in high-resolution spectrometer images.

5-6-1-2. Comparison Spectra of BSC from MFC with Other Parts of the World

Rogers and Lange (1972) formulated that only 4 out of 42 species of lichens from south eastern Australia were endemic to Australia. They found many species in common with those from arid regions of Algeria, Israel, Europe, Canada and Arizona. This indicates that reflectance characteristics of BSC may be similar and applicable throughout the world's arid and semi-arid regions, particularly in different parts of Australia.

BSC spectral characterization has mostly been conducted in the Negev desert in a cyanobacteria-dominated area (Karnieli & Tsoar, 1995; Karnieli & Sarafis, 1996; Karnieli *et al.*, 1996; Karnieli *et al.*, 1997; Karnieli *et al.*, 1999), some in the USA (Clark *et al.*, 1993a; 1993b; Kokaly *et al.*, 1994), one in China (Chen *et al.*, 2005) and some in Australia (O'Neill, 1994b; Lewis *et al.*, 2001; Fildes, 2005). All were considered to compare with the derived BSC groups spectra, apart from the habitat differences.

Karnieli *et al.* (2001) reviewed cyanobacteria-dominated soil spectra in Israel: visible and NIR regions showed brighter spectral values in comparison with vascular plants and were mostly similar to the soil spectra. Moreover, they stated that their results of spectral characterization were similar to the USA. Results of my study showed that spectral pattern of BCL, BCM and Tall Mosses are completely in contrast with those from Israel's and the USA. My spectra have darker values than both the soil and vascular plants (woody plants, perennial herbages and annuals) in visible and NIR regions however, Scaly, Crusty and Leafy Lichens have almost the same brightness values as those from Israel and the USA. These groups have brighter spectral values than vascular plants and are similar to the bare soil in the visible region. The spectral patterns in the NIR region are also different from the Negev results. From these results it can be concluded that the CI (2-10-4), which is mainly based on the blue spectra, will give inconclusive significant results for BSC detection in an area like MFC. See Chapter 7 for the results of image data for the CI results.

BCL and BCM are similar to the results of the spectra for lichen and moss spectra in the visible region in Chen *et al.'s* (2005) study. The lichen spectra in the NIR region also has a similar pattern to the results in Chen *et al.'s* (2005) study, however the moss spectra are slightly different. My results for Scaly, Crusty and Leafy lichens are completely different, in both the magnitude and pattern, from Chen *et al.'s* (2005) study. Chen *et al.* (2005) derived a spectra for algae which is different from all the BSC groups of this study. By comparing derived spectra from my study and Chen *et al.'s* (2005) study, although there are some similarities, the highest

probability is that their index (BSCI) will be poor for BSC detection at MFC because of the algae (which was not distributed at MFC), Crusty, Leafy, Scaly and NIR differences of moss spectra. See Chapter 7 for the results of image data for the BSCI.

O'Neill (1994b) derived one BSC spectrum in comparison with other land covers. O'Neill's results vary from those of the Negev desert, particularly in the visible region, showing more similarity with plant spectra from a brightness perspective. O'Neill's study gives completely different results with the Scaly, Crusty and Leafy Lichens compared with my results. However, O'Neill's result is close to those of my black BSC spectra. It should be noted that there are differences between the BCM and Tall Mosses with BCL spectra, particularly in the NIR region. Lewis *et al.* (2001) derived a single spectrum for BSC with an almost flat "red edge", which, in comparison with the results of this thesis is mostly similar to the BCL with more dark values in the visible region; however, the pattern in the NIR region is different. It is different from the derived mosses spectra of my study and Chen *et al. 's* (2005) results. From the results of my study, in dry conditions nearly 62% of BSC cover could be assumed to be the same as Lewis *et al.*'s (2001) spectrum for BSC. However, other spectral groups are different from that spectrum. O'Neill (1994b) discussed the effects of moisture which can cause BSC to start to grow with a resulting change in the spectral signature. In wet conditions spectral characteristics regarding the sharp "red edge" for wet BSC are different from the other studies and support the results of O'Neill's (1994b) study. However, there is little published material on spectral analysis of wet BSC, and from those, to my knowledge, very few using BSC groups compare with my results.

5-6-1-3. Comparison between the Spectra of BSC Groups and Other Land Covers in Dry and Wet Conditions

Similarities in brightness exist between the spectral patterns of dry bare soil with the various groups of BSC including Leafy, Scaly and Crusty Lichens with 17% cover. The similarities, which occur in the green, red, and NIR regions, are considerable. These are the wavebands that are commonly used for indices such as the NDVI, PD54 and SSI for rangeland monitoring. Thus, there is the possibility of misinterpretation of 17% of BSC by these indices. Results of my study are contrary to results of the Negev's studies (Karnieli & Tsoar, 1995; Karnieli *et al.*, 1999). My results emphasise that the main problems of MFC for individual BSC groups is not the spectral similarity between the bare soil and BSC groups. These results support the results of O'Neill's (1994b) study that in Australia, distinguishable spectral patterns exist for BSC (for more than 82%) from bare soil. However the main problems are the spectral similarities between shadow, litter and vascular plants, particularly senescence woody plants such as *Maireana* spp., leading to

the high possibility of misinterpretation between these components. These problems arise from the spectral similarities between litter and black BSC group with 62% cover. Alternatively, they arise from very close spectral patterns and brightness values for 82% cover of BSC in the visible region with shadow data. Finally, they can arise from close spectral value for NIR and red regions between vascular plants and BSC groups with 82% cover. Thus, using a method which can discriminate brightness value of litter, shadow, soil and vascular plants from BSC groups is important. From these results, radiometric calibration, particularly sun standardization is a critical stage to remove the shadow effects of the target area (Ch.7). If calibration cannot remove the shadow effects, then BSC cover will be over estimated. Using a method with sensitivity to the NIR for separating vascular plants from BSC is important, particularly if the aim of remote sensing is cover estimation for biomass and productivity calculations.

By contrast, in wet conditions, similarity between BSC groups and bare soil because of the chlorophyll contexts, "red edge" and brightness values are considerably reduced and support the results of O'Neill's (1994b) study that there are different spectral characteristics between wet BSC and soil spectra in Australia. Regarding this reduction, it seems that the value of indices such as the NDVI should be considerably different from bare soil (Ch. 6). More importantly, misinterpretations in the wet condition for 82.68% of BSC groups with bare soil, because of the "red edge" and different spectral patterns, are considerably reduced. The only exception is BCL which has a similar curve pattern with bare soil, but different brightness values. BCL could therefore be a possible group to create difficulty in certain indices. Other land covers are almost similar in wet conditions, however, the similarities between wet BSC and vascular plants are increased in wet conditions, and thus the possible misinterpretations between those could be considerable.

5-6-2. Effects of Dry and Wet BSC in the Remotely-sensed Data and Existing Indices

5-6-2-1. Effects of Background Soil on the "BSC Pattern Spectra" (BSC Communities with Background Soil) and in Turn on Remotely-sensed Data

The discussion so far has been based on the spectra of individual BSC groups. As reviewed in Section 2-8-4 one of the limitations of remotely-sensed methods for arid and semi-arid rangelands is sparse vegetation cover, thus there is a high background soil effect on the remote sensing signals (Huete & Jackson, 1988; Pickup, 1989; Smith *et al.*, 1990; Okin *et al.*, 1999). These issues, for current remote sensing technologies, create difficulty in the image processing to distinguish the real extent of the biological components, to separate different targets and finally to separate the natural variations from human-induced variables. The same problem occurs for BSC, where biological components cover canopy exceed more than 20 to 45%; thus there is the

possibility of the effects of soil background in the overall remote sensing of these components. Results show that there are very high effects of background soil on the BSC spectra as similar to the spectra of bare soil. These results support the results of the Negev studies (Karnieli & Sarafis, 1996; Karnieli *et al.*, 1996), which showed that BSC spectra in dry conditions is similar to the spectra of dry bare soil. However, differences exist in wet conditions.

Although this study has not covered hyperspectral datasets to conclude the benefits or drawbacks of selecting "BSC pattern spectra", there are very large variations between the spectra of different BSC groups. Lewis *et al.* (2001), and Fildes (2005) have divided BSC into one or two groups for endmember selection using hyperspectral datasets. It seems that they used the "pattern spectra" of the BSC rather than the specific BSC groups or species. Overall, it is not clear which groups of BSC have been used in their endmember selection. The main point is how much the selected endmembers are representative of the BSC, which show high variation. If spectra and endmember selection was based on the total pattern there is very high similarity between the pattern of BSC spectra with soil background. However, if they select their endmember based on one group of BSC what are the effects of other groups which show high spectral variation? Alternatively, if they have selected a black component as one group, what about the different spectral signatures of mosses versus lichen groups in dry conditions, assuming that they have selected their imagery in the dry state?

5-6-2-2. Spectral Effects of BSC on Remotely-sensed Data

BSC are widespread in different parts of the world (2-5-3), including Australia (2-5-4). The percentage cover of BSC on these areas is as high as 100% (West, 1990), 70% (Belnap, 1993), 45% (Belnap *et al.*, 2006), 32% (Arzani & King, 1994) and 27% (O'Neill, 1994b). From the results of Chapter 4 BSC cover at MFC varies from 1.69% near water to more than 36.99% at 4000 m from watering points. In comparison the percentage cover of BSC is much higher than the vascular plant cover at most of the sites. From the results of this chapter, BSC have specific spectral characteristics in comparison with other land covers and this supports the results of previous studies (O'Neill, 1994b; Karnieli *et al.*, 1996; Karnieli *et al.*, 1997; Karnieli *et al.*, 1999; Lewis *et al.*, 2001; Chen *et al.*, 2005), thus they cannot be neglected in image interpretation.

5-6-2-3. Spectral Effects of BSC on Different Indices

Some of the indices such as the PD54 (Pickup *et al.*, 1993) are based on the determination of the soil line for cover estimation. As discussed earlier, researchers in Israel have claimed that there is high similarity between BSC spectra and bare soil in dry conditions (Karnieli & Sarafis, 1996; Karnieli *et al.*, 1996; Karnieli *et al.*, 2001). Whereas, O'Neill (1994b) stated that there were large differences between bare soil and crusted soils, especially under wet conditions. However, from

the results of my study, in the simulated data space of band 3 versus band 2 of TM imagery, there were no mixed spectral patterns between individual BSC groups and bare soil spectra in the dry and wet conditions. As examined for PD54, SSI and NDVI, there is no effect of BSC spectra on the soil line in dry and wet conditions. However, dry "BSC pattern spectra" effects the soil line and their spectral value is almost the same as bare soil. There are also some promising results by existing indices, particularly for the SSI, that some of the BSC groups such as BCM and Tall Mosses have distinguishable patterns, and might create significant results using image data. See Chapter 7 for the results of image analyses by different indices.

5-6-2-4. PD54 is Not an Appropriate Index for Areas in which BSC Occur

The theory of soil line and background knowledge to develop soil and vegetation lines is described in Section 2-10-3. One of the best developed indices in Australia is the PD54. My results show that there was no effect of BSC on the soil and vegetation lines of this method with dry and wet BSC spectra. According to the vascular plant composition and distribution at MFC (4-5-1 & Appendix C-1), these spectral patterns can be expected for all paddocks. Thus, either near water with 1.69% BSC cover or 4000 m away from water points with 36.99% (4-5-3) in both dry and wet conditions, there is no effect of individual or BSC "pattern spectra" on the soil and vegetation lines. Thus, in the interpretation of remote sensing data using this index, BSC will not be included in the estimated photosynthetic components cover. Overall, PD54 is not a reliable index for cover evaluation in an area in which BSC occur, if we believe the ecological role and importance of these components.

5-7. Conclusions

There are very high spectral variations and complexities within BSC groups and also between them and other land covers at MFC which can create difficulties in a remotely-sensed method. However, there are some promising results which can help to discriminate these variations. BSC spectra at MFC are different from those reported from Israel and the USA, however, they are mostly similar to the spectra of China and Australia. Individual BSC spectra are more similar to litter, shadow and vascular plants in comparison with bare soil in both dry and wet conditions. However, spectra of "BSC pattern" although having different brightness value with bare soil, have similar patterns, particularly in the data space of band 3 versus band 2 of TM imagery with soil spectra. BSC cover on the rangeland is considerable and they have different spectra and possible effects on remotely-sensed methods. There are no effects of BSC on the soil and vegetation lines in dry and wet conditions in the data space of band 3 versus band 2 of TM imagery. However, "BSC pattern spectra" can affect the soil line. The PD54 is not a reliable

index for an area where BSC are common, unless there is an aim to define vascular plant detection by neglecting the ecological role of them and their benefits for rangeland ecosystems. Moreover, there could be some limitations for the application of the CI and BSCI for BSC detection at MFC. There are some promising results using the SSI for BSC detection.

CHAPTER 6

6. GROUND-LEVEL SPECTRAL MODELLING FOR BSC DETECTION

This chapter
This chapter presents ground-level spectral modeling for BSC detection. Initially some experiments were conducted for index selection and for examining the index value differences within BSC components and between different land covers. Ground-level spectra were used to model the effects of BSC on the grazing gradient patterns (models). Finally, moisture stability experiments for modeling BSC detection were considered.

6-1. Introduction

Some of the previous studies have considered BSC in ground-truthing and endmember selections (Cameron & Lewis, 1996; Lewis *et al.*, 2001; Fildes, 2005), however there is little evidence of BSC spectral analysis and ambiguity about the role of BSC in the image processing stages. Moreover, little understanding exists about the effect of BSC on the grazing gradient models. Furthermore, in the cases where BSC was taken into account in the image processing, they selected both multispectral and hyperspectral images at the time in which BSC were dry. Overall, there is less consideration and understating about the real extent and effects of BSC on remotely-sensed data (Karnieli *et al.*, 2001).

6-2. Review of Relevant Theory and Research

6-2-1. Ground-level Spectral Modeling

Much is known about biophysical processes of vascular plant relationships derived from the studies of controlled and uncontrolled environmental manipulation of individual plants, or from experiments involving vegetation contained in small field plots (Field & Ehleringer, 1993; Rundquist, 2000; Rundquist, 2002; Karnieli, 2003). Spatial variations in environmental conditions and nonlinearities in process dynamics complicate this task (Wessman, 1992; Friedl, 1997). Moreover, variation in vascular plants is a considerable issue across the surface of the land which results from interactions among biological functions and mixed structures (Rundquist, 2000). Complicating matters is the fact that such processes are dynamic and interactions among them vary in both space and time (Wessman, 1992; Karnieli, 2003). Further, change in one process potentially influences the operation of others (Rundquist, 2000).

Advancing the knowledge of how these interwoven dynamic mechanisms influence photosynthetic elements is challenging, but of great importance in recognizing and predicting warning signs of environmental change (Wessman, 1992). Likewise, cost and time limitations make site-level photosynthetic elements-based monitoring over broad geographic areas unrealistic (Rundquist, 2000).

According to these limitations in land cover detection, using ground-level remote sensing has been increasingly considered to define variations and a possible way of using the advantages of remote sensing technologies (Karnieli *et al.*, 1999; Rundquist, 2000; Richardson *et al.*, 2001; Rundquist, 2002; Couteaux *et al.*, 2003; Karnieli, 2003; Richardson *et al.*, 2004). However, non-vascular plants and the effects of them on interactions among biotic and abiotic elements, particularly bare ground in arid and semi-arid environments, were less considered. Apart from some studies in Israel (Karnieli *et al.*, 1997; Karnieli, 2003; Burgheimer *et al.*, 2006a), there is little information about remote sensing of BSC with most previous studies and no subsequent modelling impacts on the mapping process.

As reviewed in Section 2-10-1 there is increasing evidence that a given index cannot be accurately transformed between field and satellite scales in linear approach (Quattrochi *et al.*, 1997; Goodin & Henebry, 1998; Goodin & Henebry, 2002). However, it can assist in understanding the effects and characteristics of each land cover on a given index (Rundquist, 2000). Moreover, ground-level spectral modeling is a common procedure for development of a remotely-sensed method (Pickup & Nelson, 1984; Pickup *et al.*, 1993). For example, indices such as the SSI (2-10-2) and PD54 (2-10-3) are based on close-range radiometry in central Australia, and then used in analysis of image data. These types of indices (e.g. NDVI, PD54 and SSI) were developed in the areas in which BSC were not common. As mentioned in Section 6-1, studies such as Cameron and Lewis (1996) used these indices in the area in which BSC occur without ground-level spectral modeling. They used remote sensing data for image processing and then correlated results with ground collected cover for the employed indices including the PD54 (Pickup *et al.*, 1993), NDVI and SSI. As described in Section 2-10-1 the problems are that index value often is not a product of the process with which it is correlated (Huete, 1988; Briggs *et al.*, 1997; Carlson & Ripley, 1997).

6-2-2. Moisture Contents

Although, remote sensing is increasingly being utilized in observing and detecting moisture on a regional to global scale, application of remote sensing in rangeland assessment have avoided the selection of images in which soils were wet (Bastin *et al.*, 1993a; Pickup & Chewings, 1994).

This thesis aimed to consider the phenological stages of BSC, annuals and perennials, thus moisture consideration, particularly in image selection for growth stage of BSC, was inevitable.

The horizontal and vertical distributions of soil moisture exert control over the partitioning of incoming radiant energy into latent and sensible heat fluxes via evaporation and transpiration by plants (Bosworth *et al.*, 2003). The timing and magnitude of these horizontal and vertical transports of moisture are important determinants in the geochemical cycling of nutrients, the availability of soil water for biotic elements growth and more importantly, it can affect the spectral signature of remotely-sensed data (Liu *et al.*, 2003).

Moisture effects BSC. For example, during a rainfall event, the polysaccbaride sheaths of the cyanobacteria species can quickly absorb several times their weight in water (Belnap & Gardner, 1993). Various lichens are capable of rapidly absorbing from 1.5 to 13 times their dry weight in water, which can then be slowly used or released (Galun *et al.*, 1982). Cyanobacterial and algal filament sheath material will potentially absorb eight times their weight in water (Belnap & Gardner, 1993). Moreover, they function to increase the water-holding capacity of coarse textured soils (Campbell *et al.*, 1989). Loope and Gifford (1972) found that crustose lichens decreased the percolation rate of water through the soil surface. However, pooling of water occurred due to the irregular surface structure of the BSC, resulting in less runoff from the soil surface and increased infiltration of water into the soil following penetration of the BSC. However, penetration of water through the soil surface was enhanced when mosses were present (Eldridge & Rosentreter, 1999).

Overall, little information exists about the effect of moisture on the spectral variation of BSC, litter, stone and soil. O'Neill (1994b) who investigated the relationship between moisture, soil types and BSC by spectral analysis in Australia, emphasized the importance of moisture for soil and BSC detection. Karnieli *et al.*(1996), Karnieli (2003) and Burgheimer *et al.* (2006b) reported that there is little effect of soil moisture in the NDVI value of soils in comparison with BSC in the Negev desert.

6-3. Aim of Chapter

Overall, there is ambiguity about the role of BSC in different indices and derived gradient patterns when utilizing a remotely-sensed method. Hence, this chapter, by considering these issues, aimed to establish the effects of BSC in different situations on the grazing gradient patterns. For this purpose the NDVI and SSI were examined to clarify the effects of BSC on the grazing gradient models.

There are also some other considerations in this regard: Firstly, as mentioned earlier, cover components have already been used for cover estimation by remotely-sensed methods to

conceptualize land degradation (Bastin *et al.*, 1993a; Pickup *et al.*, 1994). If BSC were misinterpreted then results could be estimated with misclassification of degraded areas. Secondly, estimated cover data were used to model the quantity of fodder available for grazing (Tucker *et al.*, 1985; Tueller, 1995, 2001); the risk of erosion (Pickup & Nelson, 1984; Pickup *et al.*, 1993); surface hydrology classification and soil conservation (Schultz & Engman, 2000), and the fuel load in bushfire hazard situations (Allan *et al.*, 2003). Thus, the amount of estimated cover could be the main source of error in these types of models in areas in which BSC occur. In order to understand how BSC spectra affect the cover estimation of rangeland features in dry and wet conditions, the following objectives were provided:

1. Examine different index values for varying BSC components in dry *vs.* wet conditions
2. Compare index values for BSC *vs.* other land covers in dry *vs.* wet conditions
3. Compare surfaces (plot) covered with BSC *vs.* bare ground using ground-level spectral analyses (pattern analyses)
4. Model the possible grazing gradient patterns with and without BSC, and
5. Model the temporal change in spectra as a function of changing the moisture (for image selection).

6-4. Methods

Ground-based data collections are described in Chapters 3 and 4, and details of spectra collection in the laboratory and field conditions in Chapter 5.

6-4-1. Spectra Collection

Spectra of the species level were collected (at least 10 samples for each component) in the laboratory under artificial illumination and at the BSC group level in the field (5-4). In addition, spectra of soil, stone, litter, and vascular plant were also collected using the same procedure. In the first stage spectra were collected in the range of 350 to 1100 nm with 3.3 nm intervals, followed by noise removal reducing the spectral range to 400 to 900 nm. In the second stage, collected spectra were resampled to synthesise Landsat TM data.

6-4-2. Index Selection (Step 1)

There is a large variety of remotely-sensed methods, which have been developed for rangeland monitoring. The selection of a method or index is a crucial step because of the possibility of huge numbers. Index selection in this chapter was mainly focused on the developed indices in Australia, developed indices for BSC detection in the world and ongoing use of these indices. Thus, different indices including PD54, SSI, CI (2-10-4), BSCI (2-10-5), Simple Ratio (SR),

NDVI and some other indices (Table 2-5) were considered for this part of the study. Finally, from those, by consulting the results of Chapter 5, four indices including NDVI, CI, BSCI and SSI were selected for this chapter in the first stage.

6-4-3. Differences between Dry and Wet Conditions for Index Selection (Step 2)

Moisture effects on the different indices such as NDVI, CI, BSCI, and SSI by field-collected spectra at the BSC group level were considered as a pilot study for a preliminary understanding of spectral value change from dry to wet conditions for the final stage of index selection. Results of this step showed there were two groups of indices with positive versus negative values. From the positive groups, the NDVI had a stable trend with distinguishable pattern from dry to wet conditions for land covers. From the indices with negative values, SSI had the most stable trend and distinguishable pattern. Moreover, by considering some analyses in Chapter 5, finally the NDVI and SSI were selected for ground-level spectral modelling. They were also selected because there are many ongoing projects using these indices, particularly the NDVI at the local, regional, national and international level (2-10-1). Therefore, the NDVI in all sections of this chapter and SSI in some sections were used for the investigation of the effects of BSC in the grazing gradient patterns.

6-4-4. NDVI Differences between Dry and Wet Conditions for BSC Components

For the validation of spectral value differences for BSC species in dry versus wet conditions, this part of the study was conducted to examine and define the magnitude of NDVI value differences to conclude the possibility of detecting or considering these components in the ground-level spectral modelling. This part examined the NDVI value differences between BSC species and other land covers. As mentioned earlier, moisture can affect BSC and other features simultaneously. Thus, bare soil, litter and stone, all of which could be affected by moisture, were considered in dry and wet conditions under laboratory and field conditions for comparison with BSC species.

6-4-5. NDVI Differences between BSC and Other Land Covers in Dry *vs.* Wet Conditions

To avoid the effect of moisture, previous studies have selected their imagery a considerable time after rainfall when soil, litter, stone and BSC were in a dry condition. Bare soil, vascular plants, litter and BSC groups were considered to examine the index value differences in dry versus wet conditions using field-collected data. In this stage, different soil colour and texture spectra were also considered in each site in the field as mean soil spectra.

6-4-6. SSI Differences between BSC and Other Land Covers in Dry *vs.* Wet Conditions

In addition to the preliminary comparison of different land covers using different indices, spectral values of different land covers were simultaneously compared to magnify the differences for the SSI. In this comparison, field-collected dry versus wet spectra for different BSC groups and other land covers were considered to understand how the index value changes from dry to wet conditions.

6-4-7. Index Value Comparison between "BSC Patterns" and "Bare Ground Patterns"

In dry conditions BSC spectra is the same as bare soil and there is a high probability of misinterpretation between them (Karnieli & Sarafis, 1996; Karnieli *et al.*, 1996; Karnieli *et al.*, 2001). The results of Chapter 5, particularly in the simulated data space of TM band 3 versus band 2, show that for individual BSC samples there is no overlap with bare soil spectra. However, "BSC pattern spectra" have shown ambiguities of the possible mixture between BSC and bare soil (5-5-4 & 5-5-5). It may be that BSC communities with bare soil background have different behaviour and spectral characteristics in response to moisture in comparison with the individual BSC groups or species. Thus, to clarify this ambiguity spectra from a surface with BSC communities (BSC > 30%) versus spectra of a surface with bare soil (BSC <1%) were taken from 50 cm height (Figure 5-2). This experiment was conducted to determine; if there were any distinguishable effects or change if "BSC pattern" instead of individual BSC are considered. See Section 5-4-4 for details of the spectral collection for the pattern.

Overall, 24 sample sites (0.5 × 0.5 m) were selected with 12 sites with bare ground and 12 sites with "BSC patterns". These sites were then used for applying different amounts of the artificial rainfall for growth (greenness) stability of BSC. Additionally, 12 stone and 12 litter samples were simultaneously used with artificial wetting (under the same environmental conditions) to discover the NDVI value differences in dry and wet conditions. The spectrometer was fixed for 3 scans average for each sample spectra.

6-4-8. Modelling Grazing Gradient Patterns With and Without BSC

This stage was implemented in order to examine the potential effect of BSC in the remote sensing data and detection of these components using collected spectra under field conditions. Collected dry and wet spectra of individual BSC, soil, litter and vascular plants (Table 6-1) were used to derive grazing gradient models for each paddock by the percentage cover for each site. According to the studies in Australia, including South Australiain rangelands, which were predominantly undertaken using Landsat datasets (Chs.2 & 7), this part of the study was

conducted to evaluate the collected spectra for selected indices (NDVI and SSI) based on the synthesized TM datasets.

Table 6-1. Main land covers and BSC groups, which were used in this chapter for grazing gradient modelling and the number of spectral samples for each group

Land covers						Dry spectra, n =	Wet spectra, n =
Bare soil						108	70
Litter						40	15
Photosynthetic elements	Vascular plants	Perennials	Woody plants*		Bluebush (*Maireana sedifolia*)	86*	86*
					Blackbush (*Maireana pyramidata*)	71	71
					Saltbush (*Atriplex vesicaria*)	59	59
					Acacia spp.	62	62
					Other bushes	9	9
			Herbage		Forbs	16	16
					Grasses	5	5
		Annuals*			Forbs	11*	11*
					Grasses	3	3
	BSC (Morphological/ Functional groups)				Black Common Lichens (BCL)	52	12
					Black Common Mosses (BCM)	42	9
					Scaly Lichens	66	13
					Leafy Lichens	46	11
					Crusty Lichens	71	25
					Tall Mosses	46	10
BSC patterns						26	15

* the same spectra for dry and wet conditions

6-4-8-1. Procedure of Grazing Gradient Analysis

The question stated in the grazing gradient analysis was, if there are different spectra or index values for individual BSC and other land covers, do they affect the grazing gradient patterns? The percentage cover of the various land covers was estimated by the line-intercept method (Chs. 3 & 4) during the wet and dry seasons of 2 consecutive years (Appendices A-1 & C-1), enabling the estimation of cover of annual, perennial and BSC on the study sites. Data were classified according to the different BSC groups, vascular plants, soil and litter quantity for each site (Chs.3, 4 & Table 6-1). In order to assess the relative contribution of each feature to the overall ground features spectra of a study site, for dry and wet conditions, a linear mixture model (Settle & Drake, 1993; Burgheimer *et al.*, 2006a) was used to calculate a weighted index value for each site.

$$Index_{Wi} = \sum_{j=1}^{n} (fjMij) \qquad \text{equation 6-1}$$

where $Index_{Wi}$ is the weighted index in the i-th situation, *fj* is the fraction of area covered by j-th cover type, *Mij* is index of the j-th cover type in the i-th condition and *n* is the number of cover types.

Grazing Gradient Models

In order to investigate the effect of BSC in the remotely-sensed methods, they were taken into account in the grazing gradient model calculation using different models. Overall, five possible models were derived for dry and wet conditions by considering the effect of BSC (Table 6-2). There was the possibility of deriving other model(s) with different indices and simulating different sensors from collected ground-level cover and spectral data. However, it was decided that calculation of grazing gradient patterns of the NDVI and SSI, for TM imagery, by these five models was sufficient to understand the problem.

Vascular Plant Model (Without BSC) (Model 1_a-b)

This model was conducted, assuming image interpretation does not take the BSC into account. Calculation was undertaken for dry season versus wet season without BSC. The weighted indices values (NDVI and SSI) for each site for dry and wet seasons were calculated according to Table 6-2. As this Table shows, for dry season, bare ground and litter were considered using dry spectra. Vascular plants for the dry season were considered only using the perennials (Table 6-1) spectra. For the wet season dry spectral value of bare soil and litter were also considered. For this season perennial and annual spectra were considered for vascular plants (Table 6-1). In this model for dry and wet seasons, BSC were not included in the indices calculation. They were assumed as bare ground, with their percentage cover added to the bare soil, and then, the weighted index value calculated as [%cover of bare soil (bare soil +BSC) × index value of soil] (Table 6-1). Weighted indices for dry and wet conditions were calculated according to Table 6-2. It should be noted that the majority of the perennial plants at MFC are not deciduous. In spite of this fact, it is obvious that the greenness / cover value of the perennials could change with a rainfall pulse, or from dry to wet seasons, but measuring phenomenon of this, particularly in respect to the variety and mixture of vascular plants, is difficult or may be impossible. Thus, by understanding these issues annual plants were considered as a variable element for indices in the dry and wet conditions to conceptualize this model. Overall, in five models, perennial spectra for dry and wet conditions were considered equal for both situations and annual were used only for the wet season.

Table 6-2. Grazing gradient models and index value calculations from land covers

Model	Indices calculation in dry and wet conditions
Model 1_a-b: (without BSC)	**a_ Dry season index value** = ^{Dry} **Bare ground** $^{(1)}_{index\ value}$ + ^{Dry} **Litter** $^{(2)}_{index\ value}$ + **Perennials** $^{(3)}_{index\ value}$
	b_ Wet growing season index value = ^{Dry} **Bare ground** $_{index\ value}$ + ^{Dry} **Litter** $_{index\ value}$ + **Perennials** $_{index\ value}$ + **Annuals** $^{(4)}_{index\ value}$
Model 2_c-d: (BSC as one group)	**c_ Dry season index value** = ^{Dry} **Bare ground** $_{index\ value}$ + ^{Dry} **Litter** $_{index\ value}$ + **Perennials** $_{index\ value}$ + ^{Dry} **BSC** (one value)$^{(5)}_{index\ value}$
	d_ Wet growing season index value = ^{Dry} **Bare ground** $_{index\ value}$ + ^{Dry} **Litter** $_{index\ value}$ + **Perennials** $_{index\ value}$ + **Annuals** $_{index\ value}$ + ^{Dry} **BSC** (one value)$^{(5)}_{index\ value}$
Model 3_e-f (BSC in dry conditions)	**e_ Dry season index value** = ^{Dry} **Bare ground** $_{index\ value}$ + ^{Dry} **Litter** $_{index\ value}$ + **Perennials** $_{index\ value}$ + ^{Dry} **BSC** $^{(6)}$ index value
	f_ Wet growing season index value = ^{Dry} **Bare ground** $_{index\ value}$ + ^{Dry} **Litter** $_{index\ value}$ + **Perennials** $_{index\ value}$ + **Annuals** $_{index\ value}$ + ^{Dry} **BSC**$^{(6)}$ *index value*
Model 4_e-g (Dry condition model [except annuals/e] *vs.* all land covers in wet condition model/g)	**e_ Dry season index value** = ^{Dry} **Bare ground** index value + ^{Dry} **Litter** index value + **Perennials** index value + ^{Dry} **BSC**$^{(6)}$ index value
	g_ Wet growing season index value = ^{Wet} **Bare ground** index value + ^{Wet} **Litter** index value + **Perennials** index value + **Annuals** index value + ^{Wet} **BSC**$^{(6)}$ index value
Model 5_e-h (BSC detection model)	**e_ Dry season index value** = ^{Dry} **Bare ground** $_{index\ value}$ + ^{Dry} **Litter** $_{index\ value}$ + **Perennials** $_{index\ value}$ + ^{Dry} **BSC**$^{(6)}_{index\ value}$
	h_ Wet growing season index value = ^{Dry} **Bare ground** $_{index\ value}$ + ^{Dry} **Litter** $_{index\ value}$ + **Perennials** index value + **Annuals** $_{index\ value}$ + ^{Wet} **BSC** $^{(6)}_{index\ value}$

(1) **Bare ground index value** = (%cover of Bare ground of the site × *index value*)

(2) **Litter index value** = (%cover of Litter × *index value*)

(3) **Perennials index value** = ((%cover of Bluebush × *index value*) + (%cover of Blackbush × *index value*) + (%cover *of Atriplex vesicaria* × *index value*) + (%cover *of Acacia* spp. × *index value*) + (%cover of Grasses × *index value*) + (%cover of Forbs × *index value*) + (%cover of other vascular plants × *index value*)) / ((Bluebush *index value*+ Blackbush *index value*+ ··· + other vascular plants *index value)*)

(4) **Annuals index value** = ((%cover of Grasses × *index value*) + (%cover of Forbs × *index value*)) / (Grasses *index value*+ Forbs *index value)*

(5) **Total index value of BSC components when were assumed as one group /Pattern spectra**= ((Black Common Lichens × Pattern spectral *index value)* + (Black Common Mosses × Pattern spectral *index value)* + (Scaly Lichens × Pattern spectral *index value)* + (Leafy Lichens × Pattern spectral *index value)* + (Crusty Lichens × Pattern spectral *index value)* + (Tall Mosses × Pattern spectral *index value))* / ((Black Common Lichens pattern spectral value) + (Black Common Mosses pattern spectral value) + ··· +(Tall Mosses pattern spectral value))

(6) **Total index value of BSC components** = ((%cover of Black Common Lichens × *index value*) + (%cover of Black Common Mosses × *index value*) + (%cover of Scaly Lichens × *index value*) + (%cover of Leafy Lichens × *index value*) + (%cover of Crusty Lichens × *index value*) + (%cover of Tall Mosses × *index value*)) / ((Black Common Lichens *index value*) + (Black Common Mosses *index value*) + ··· +(Tall Mosses *index value*))

Modeling Previous Studies' Results

Lewis *et al.* (2001) conducted their hyperspectral-based study by considering all BSC components as one endmember. The concept of hyperspectral remote sensing and unmixing methods are different from the multispectral datasets and indices-based methods. However, the output of index or unmixing method for estimation of BSC cover should be the same. This study has not compared the hyperspectral or unmixing method with the multispectral or indices-based method. This study has only compared the results of including BSC groups in the gradient model versus considering all BSC as one group in the gradient patterns according to the collected data. Although, hyperspectral data were selected in dry conditions, this study has calculated gradient patterns for both dry and wet conditions. Thus, in the simulating of this model, the NDVI and SSI values of dry BSC, soil and litter for wet and dry images were considered in the weighted gradient calculation. This model, by considering the total BSC cover and BSC groups cover, was considered in two sub-models. The concept for deriving these models was what is the effect of total BSC as one group versus different BSC groups in the derived indices.

Modeling Previous Studies by Assuming All BSC as One Group (Model 2_ c-d)

Previous studies predominately considered BSC as one (Lewis *et al.*, 2001) or two (Fildes, 2005) groups. This study initially utilized the mean of all BSC spectra (Table 6-2). After the mean calculation for BSC components with pattern spectra, weighted index values were considered by taking different land covers including bare soil, litter, vascular plant and BSC into account for the index calculation (Table 6-2).

Modeling Previous Studies by BSC Groups Considerations (Model 3_e-f)

A second model was established by taking BSC groups into account when calculating weighted index values. The question for this model was; are there any differences between BSC group index values and values for total BSC cover as one group? For this purpose, the same as other models, the NDVI and SSI value of each BSC group was used in the weighted NDVI and SSI calculation for each site (Table 6-2).

Wet Conditions Model (Model 4_e-g)

This model was developed for soil, litter and BSC which were in wet conditions. The aim was to examine the moisture effect in the soil, litter and BSC. The same as previous models, perennials and annuals were considered for the wet model and perennial only for the dry model (Tables 6-1 & 6-2).

BSC Detection Model (Model 5_e-h)

The last model was based on the possibility of detecting BSC in a conditional situation. If BSC can retain moisture and growth effects longer than soil, stone and litter, what should the derived gradient pattern from remotely-sensed data be? Dry model spectral value of dry components, with the same procedure as models 3 and 4, were calculated. For the wet model, dry spectra of soil and litter were used with wet spectra of BSC (Table 6-2).

6-4-9. Modelling Moisture Stability or Stability of Greenness (Dehydration) Variations

BSC are sensitive to moisture and turn green immediately after a rainfall pulse (Karnieli, 2003). Consequently, this change is important, particularly at the beginning of the wet season or summer period when other photosynthetic elements, including annuals, have not yet germinated and perennials have not developed into progressive growth stages.

As mentioned earlier, not only will BSC change after a rainfall pulse, but also other land covers such as bare soil, litter and stone can be affected by moisture. This study planned to factor in moisture effects to determine a suitable period after a rainfall pulse for image selection and BSC detection (Model 5). Thus, an experiment based on simulating artificial rainfall with different increments of rainfall was undertaken. Moisture effects on litter, stone, soil and BSC were measured by spectra collection in the dry condition; then spectral measurements were continued in each hour after wetting for a period of 4 to 5 hours as a pilot study. These procedures were repeated in the laboratory and field for 4 to 7 days by daily measurement to determine the effect of given moisture and their spectral variations, to investigate the moisture stability (dehydration) for different land covers.

6-4-9-1. Laboratory Experiments

Laboratory experiments based on the individual BSC species, litter, soil, and stone samples were wetted (soil and BSC in saturated status and litter and stone were wetted) under laboratory conditions in 21° to 23°C. Experiments were conducted in a "darkroom", during the spectra collection using an external 1000 watt Halogen lamp (5-4-5). Spectra of different components were collected in dry conditions and then after wetting. Spectra of different components were measured at the same time each day, at the same illumination, direction and distance (5-4-5). Experiments for each day took about 4 to 6 hours and samples were stored during the experiment at a laboratory. This long period at daylight time can affect the photosynthetic characteristics and needs more consideration. After experiments samples were stored outdoors.

6-4-9-2. Field Experiments

The knowledge of climatic variables (3-2-1 & Appendix E) shows that there are strong relationships between temperature and humidity with moisture stability of soil and other components. Thus, this experiment was planned in the main seasonal patterns (European calendar) of a year. However, the spectrometer was not available for the summer, and particular winter experiments, which was very important for the conclusion of this part of the study. The first replication was undertaken from November 26 to 29th in 2004 at the end of spring with a temperature of 40 to 42°C with low relative humidity (less than 30% / Appendices E-2 & F2). The second experiment was cancelled during summer. The third experiment was conducted from April 22 to 28th in 2005 with a maximum temperature of 32°C and minimum of 15°C with relative humidity 20% to 68% (early morning and afternoon) measured using the Oregon Scientific (2004) instrument. The fourth experiment, which was planned for 15th to 25th in July 2005 because of the unavailability of the spectrometer, was cancelled. Two successful experiments were named as summer-spring and autumn datasets.

According to the rainfall analyses (3-2-1 & Appendix E), 4 rainfall categories: 5, 10, 15 and 20 mm rainfall were selected for each of three sites (3 × 5 mm, 3 × 10 mm, 3 × 15 mm and 3 × 20 mm). From each site four measurements, totally 12 measurements for each rainfall category were collected. The spectrometer was fixed to 3 scans average for each measurement. The humidity and air temperature (minimum and maximum) were measured by a weather forecast instrument (Oregon Scientific, 2004) and results were compared with the Whyalla station data during the experiment times (Appendix F2).

6-5. Results

6-5-1. Differences in Value of Indices in Dry *vs.* Wet Conditions

As described in Chapter 2, and will be discussed further in Chapter 7, a controversial issue for this study was the moisture context and its effect on different land covers. Potentially, it can create biased results in the image interpretation. Thus, in addition to the plotting of dry spectra versus wet spectra in the Cartesian data space in Chapter 5, index values were also tested in dry versus wet conditions. The question was "how does an index value change from dry to wet conditions?" This experiment assists in selection of a suite of suitable indices for this chapter, particularly for index selection for grazing gradient analysis. As mentioned, many indices were tested for moisture effects and finally four of them, by consulting the results of Chapter 5, were identified as important for BSC monitoring.

6-5-1-1. Indices Value in Dry *vs.* Wet Conditions for Main Land Covers

As can be seen from Figure 6-1a-d, two groups of indices for dry versus wet conditions can be classified as positive for "cover value" versus negative for "soil stability value". The second important point is the index value change in dry versus wet conditions. For example, the CI value for bare soil is reduced, on the other hand for the NDVI is increased, thus in the image interpretation stage these changes should be taken into account (Ch.7). Another important point for bare soil is the similar index value for the BSCI in dry versus wet conditions. Finally, the amount of change between wet to dry for bare soil is very low. In most cases, it is lower than the soil spectral noise. For stone, change is very low with a mixed pattern from index to index. Litter value for the indices such as CI, SSI and BSCI is very low but for the NDVI the amount of change is considerable. The amount of change for shadow data is considerably larger in comparison with other land covers.

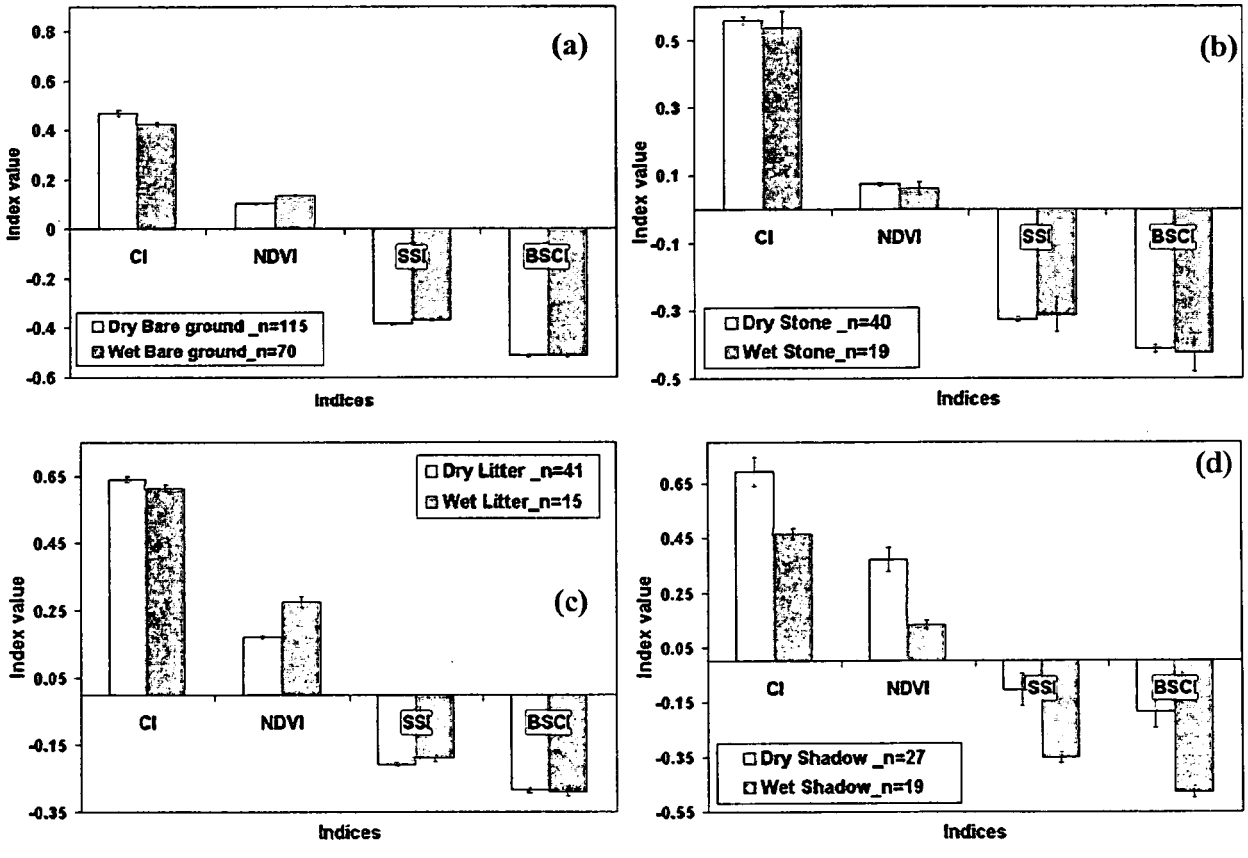

Figure 6-1. Dry *vs.* wet indices values for main land covers: a) bare soil; b) stone; c) litter, and d) shadow at MFC

6-5-1-2. Indices Value in Dry *vs.* Wet Conditions for BSC Groups

Figure 6-2a-h, shows the indices value differences for BSC groups in dry versus wet conditions. There are two groups of index values as positive for "cover value" versus negative for "soil stability value". The value of CI from dry to wet conditions is reduced with the same value for Scaly Lichens and increased for Leafy Lichens.

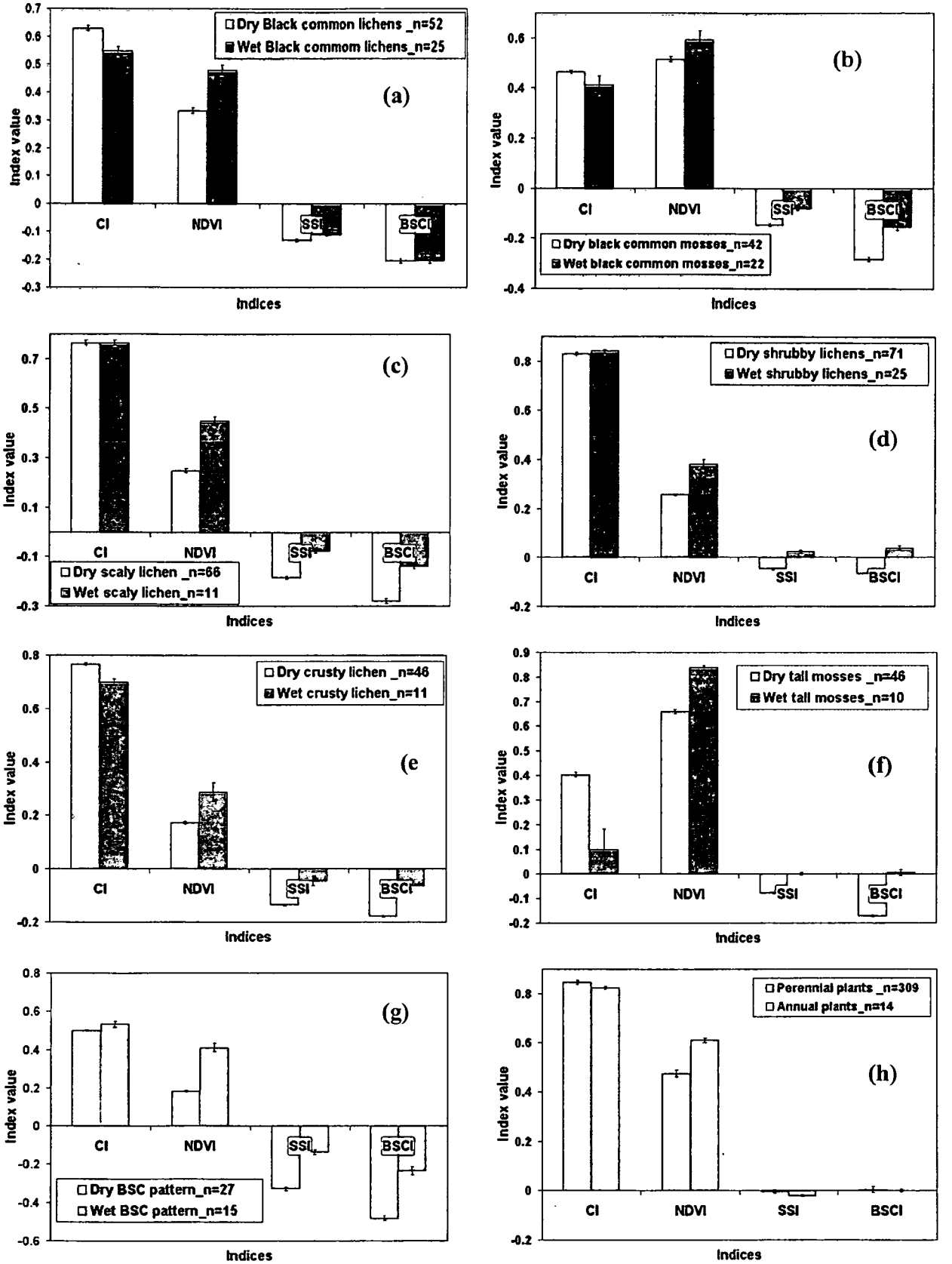

Figure 6-2. Dry *vs.* wet index values for BSC groups: a) Black Common Lichens (BCL); b) Black Common Mosses (BCM); c) Scaly Lichens; d) Leafy Lichens; e) Crusty Lichens; f) Tall Mosses; g) "BSC pattern", and h) Vascular plants at MFC

The value of NDVI is increased for all BSC groups. The SSI and BSCI in wet conditions have higher values in comparison with dry conditions for all BSC groups. Four indices values for vascular plants are presented in Figure 6-2h. This graph was prepared to understand index value differences for perennials (woody + herbage) and annuals to use in index selection for this chapter.

Overall, as mentioned earlier, four selected indices, the SSI as the representative of negative value for soil stability and NDVI as the representative of positive value for cover estimation, were selected for this chapter. Among the tested indices, the NDVI was selected for BSC spectra analyses, because of its stable pattern from dry to wet conditions. The SSI was also selected because of strong relationships with BSC cover (the simultaneous image analysis / Ch.7), and a stable pattern from dry to wet conditions. Both of the indices were used for the grazing gradient modelling.

6-5-1-3. NDVI Values in Dry *vs.* Wet Conditions in the Laboratory

Figure 6-3 is prepared to maximize the magnitude of spectral change from dry to wet conditions. The NDVI values of litter, stone and soil from the laboratory spectra are presented in this graph to compare with the magnitude of the NDVI value differences for the BSC and other land covers, which will change with moisture availability. As can be seen from the graph, the index value for all BSC species and other land covers increase from dry to wet conditions. The magnitude of change for BSC species is much larger than the other land covers. Although the magnitudes of change for other land covers in comparison with BSC species are small, they can effect the results of image interpretation, if images are selected during the wet conditions for soil, litter and stone. From the graph, one of the Leafy Lichens (*Chondropsis semiviridis* /Chos), Scaly Lichens (*Psora* spp. / Psoc and Psod), mosses (*Bryum campylothecium* / Bryc), and most of the black lichens (*Placidium squamulosum* / Plas, *Endocarpon* spp. / Ends, *Cladonia* sp / Cols, *Cyanobacterium* spp. / Cyasp1 and Cyasp2) have larger NDVI value increases in comparison. In contrast, some of the Leafy Lichens such as *Xanthoparmelia* spp. (Xanc and Xans) have the smallest change from dry to wet conditions. An important point from this graph is the smallest change value for BSC is much higher than for soil, litter and stone. Moreover, the similarity of NDVI values in dry conditions among the species such as *Collema* spp. (Clos), *Psora crystallifera* (Psoc), *Fulgensia* spp. (Fuls) and *Diploschistes* spp. (Dips) with stone, litter and bare soil (Bare ground) values is considerable.

6-5-1-4. NDVI Values in Dry *vs.* Wet Conditions in the Field

According to the identification and sample preparation problems for BSC species (3-10), spectra of BSC groups for both dry and wet conditions were collected in the field. As can be seen from

Figure 6-4, NDVI values in comparison with the laboratory data for the lichen groups are reduced (nearly 0.1). Nevertheless, field data also supports the idea that there are considerable NDVI differences from dry to wet conditions with increase in the spectral value. Moreover, the same as the laboratory results, although the magnitude of change for the NDVI of soil, stone and litter is very small, this amount can possibly create misinterpretation in the results of the image processing.

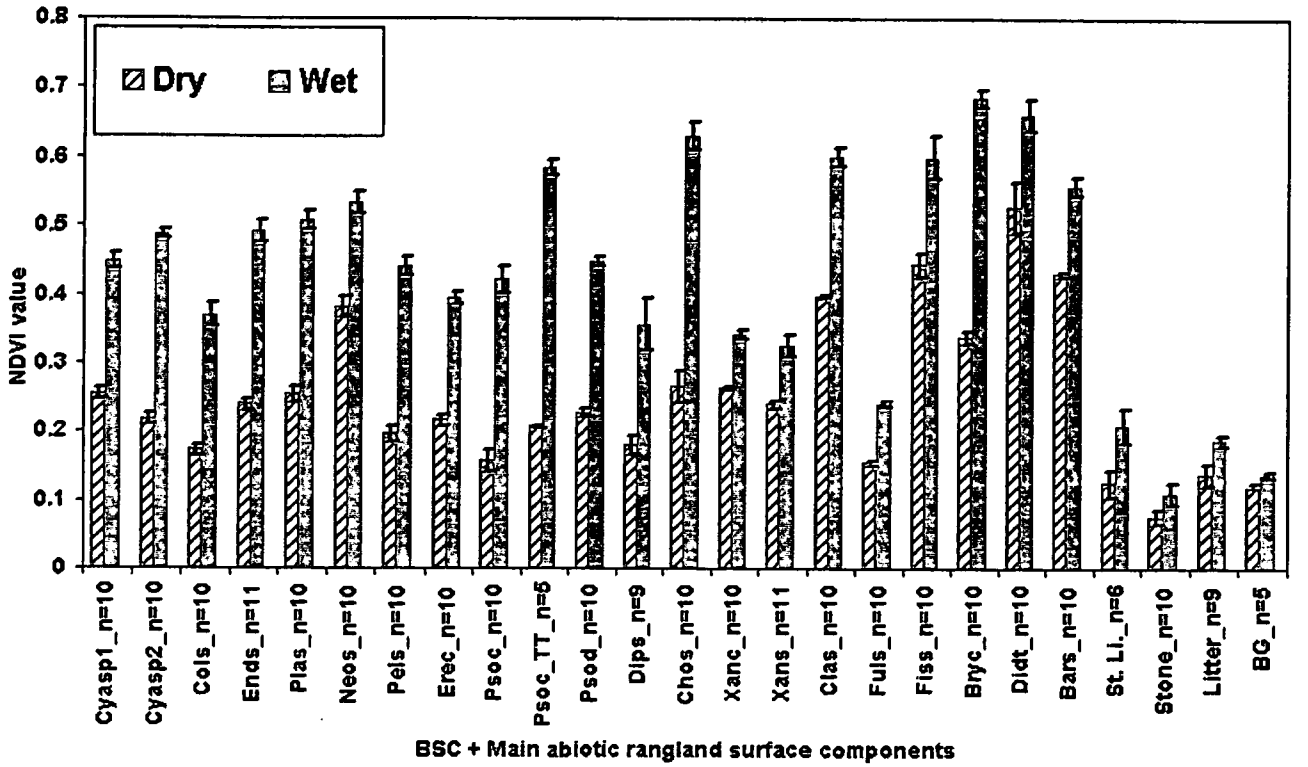

Figure 6-3. Mean NDVI value (± standard error) in dry *vs.* wet conditions of different BSC species and other land covers under laboratory condition (The full name of abbreviated name of species is given in Table 3-8).

Similarity of NDVI Value between BSC and Bare Soil

The laboratory results of the field-collected data for the NDVI supported the previous studies' claim that there are similarities between BSC and bare soil index value in dry conditions. Its values in dry conditions for most of the BSC groups are the same as bare soil and litter.

Similarity of NDVI Value between BSC and Shadow

Figure 6-4 shows the value of NDVI for bare ground and shadow versus BSC is very low. However, this amount is considerable to change the NDVI value and misinterpretation. There is very high spectral variation for shadow data, and it depends on the density of canopy cover. Presented shadow spectra (Bare ground _Shad_Blue, Bare ground _Shad_Black, Bare ground _Shad_At.v & Bare ground _Shad_ Ac.spp) are for bare ground under dense *Maireana* spp.,

Atriplex vesicaria and *Acacia* spp. respectively. The amount of variation from dry to wet conditions is small, but from the shadow of one woody plant to another is large. This variation may arise from soil colour and texture, but overall variation is related to the density of light penetration through the canopy.

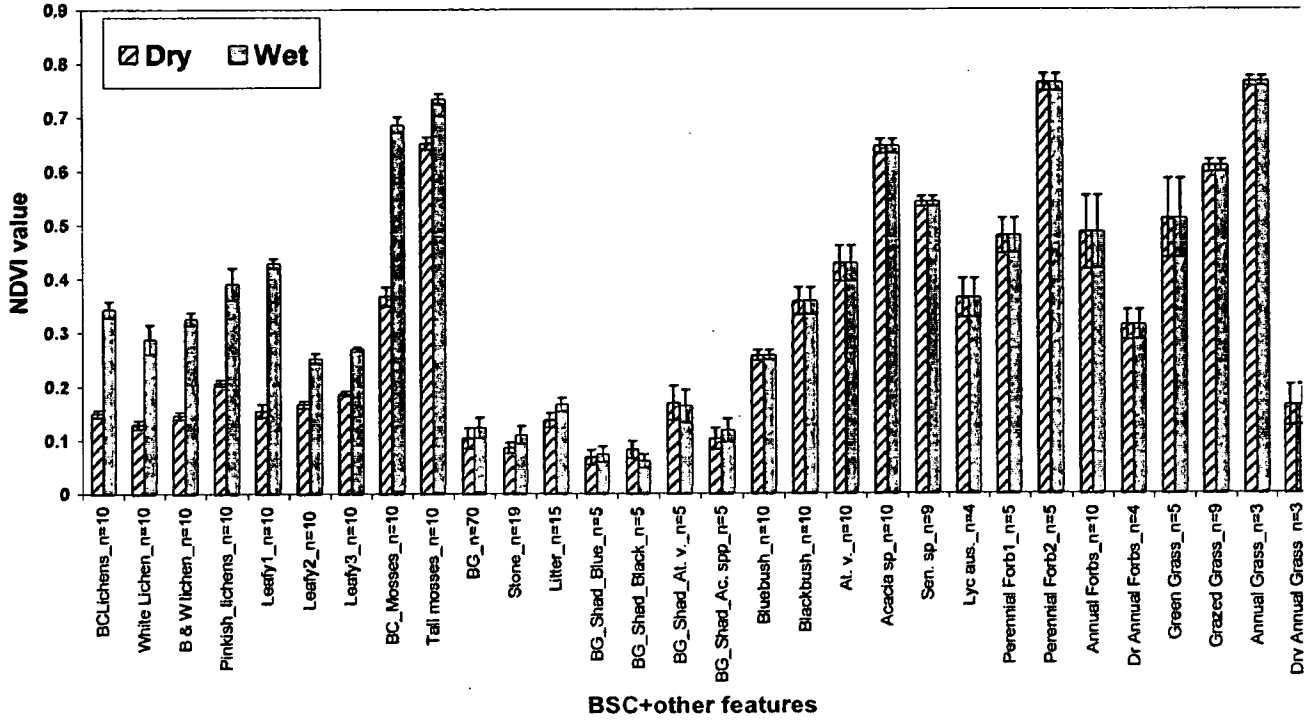

Figure 6-4. Mean NDVI value ± standard error in dry *vs.* wet conditions of different BSC and other land covers under field conditions at MFC (The full name of abbreviated name of species is given in Table 3-8 / the same spectra are used for vascular plants in dry & wet conditions / BG=bare ground)

For example, according to the canopy cover variation in *Acacia* spp. and *Atriplex vesicaria,* there are large NDVI variations in comparison with the *Maireana* spp. As Figure 6-4 shows, *Acacia* spp. has the highest amount of light penetration in comparison with *Maireana* spp. According to the large NDVI variations for shadow data, there is the possibility of misinterpretation between the shadow and BSC.

Similarity of NDVI Values between BSC and Vascular Plants

Figure 6-4 shows NDVI values of different vascular plants versus different BSC. These spectral values are the mean spectra of different samples. If NDVI value of different vascular plants in different statuses such as vigour, senescence, grazed and ungrazed is taken into account for model calculation, then variation will be increased considerably (See Section 5-5-1). However, by considering the presented data, there are very large variations between species, which can

create misinterpretation. As the graph shows, there is high possibility of misinterpretation of dry BSC, particularly Black Common Mosses (21% cover) with *Maireana* spp. and other vascular plants at the MFC. Moreover, NDVI value of Tall Mosses is similar to the *Acacia* spp. and grasses.

6-5-1-5. SSI Values in Dry *vs.* Wet Conditions in the Field

Figure 6-5 shows the SSI value for different BSC groups and other land covers from field-collected spectra. There are mixed patterns for spectral values as mostly negative and some positive. BSC pattern has the largest differences between dry to wet conditions and in the second and third level Crusty and Scaly Lichens have the largest variations. According to the different percentages cover of different land covers there would be a mixed pattern for derived grazing gradient patterns for defined models (6-4-8).

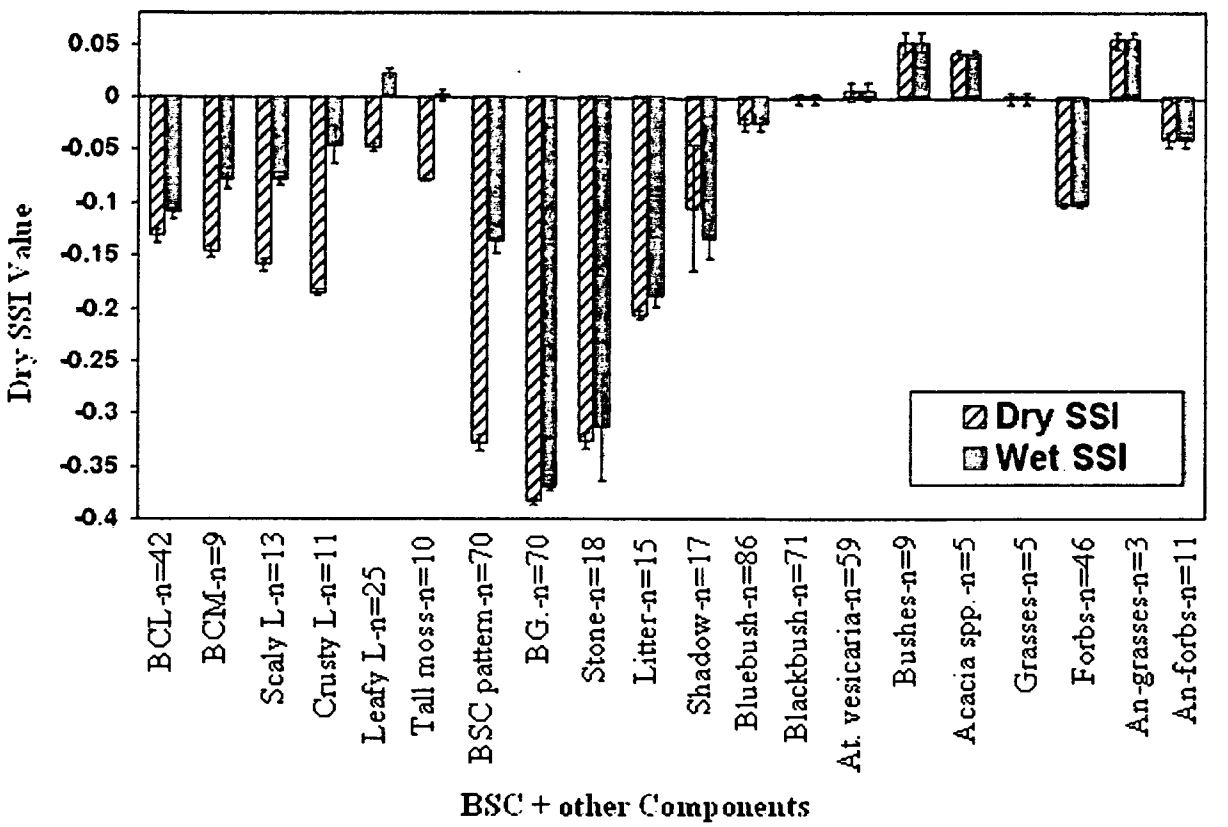

Figure 6-5. Mean SSI value (± standard error) in dry *vs.* wet conditions of different BSC and other land covers under field condition at MFC, (The same spectra are used for vascular plants in dry & wet conditions/ BCL=Black Common Lichens, BCM = Black Common Mosses, BG= Bare ground)

6-5-2. BSC Pattern (Plot) Analysis

To test the hypothesis of BSC effects when mixed with a bare soil background (2-8-4 & Ch.5) on remote sensing signals in dry and wet conditions, an additional experiment was conducted on the study area. Figure 6-6 shows BSC pattern analyses results under different moisture conditions.

For dry conditions there are small NDVI differences between areas covered by BSC and the area without them. By contrast, there are large NDVI differences for the areas covered by more than 30% BSC cover versus areas without them (area less than 1%). Although the graph shows a relationship between the amount of moisture and NDVI value, this change is related to the percentage cover of BSC and composition rather than the amount of moisture and in dry conditions this trend also occurs. Two important findings from pattern analyses can be classified as: firstly, according to the small differences between the NDVI values in dry conditions, there is a high probability of misinterpretation of BSC as bare ground or vice versa using indices such as the NDVI. Secondly, the magnitude of change for NDVI for the pattern of BSC in comparison with the bare soil samples is very large from dry to wet conditions.

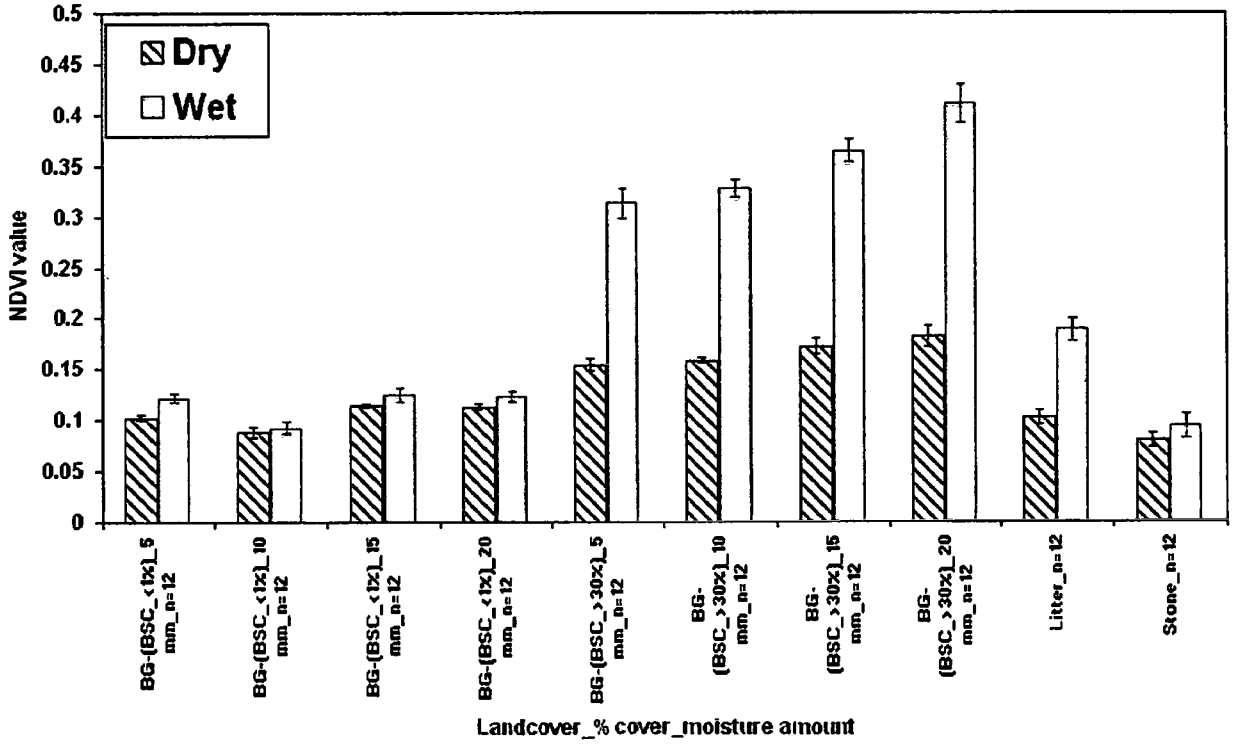

Figure 6-6. Mean NDVI value (± standard errors) for bare soil samples (<1% BSC) and four BSC samples cover (>30% BSC) in dry *vs.* wet (wetting with four amounts; 5, 10, 15 & 20 mm) conditions. In addition, mean NDVI value of litter and stone are presented in dry and wet conditions for comparison (BG = Bare ground)

6-5-3. Grazing Gradient Models

6-5-3-1. Normalized Difference Vegetation Index

Figure 6-7 shows five-weighted NDVI-based grazing gradient models for collected spectra and ground cover data. The first model (**a** & **b**) was developed to examine the effects of BSC in the remotely-sensed method (NDVI) by omitting them from the grazing gradient model. This model shows "no gradient" (2-7) for dry season and "inverse gradient" (2-7) for wet growing season with high difference cover values in comparison with other models. In comparison with the

results of Chapter 4 (4-5-1, 4-5-2 & 4-5-3), this model is mostly representative of the vascular plants in dry and wet seasons.

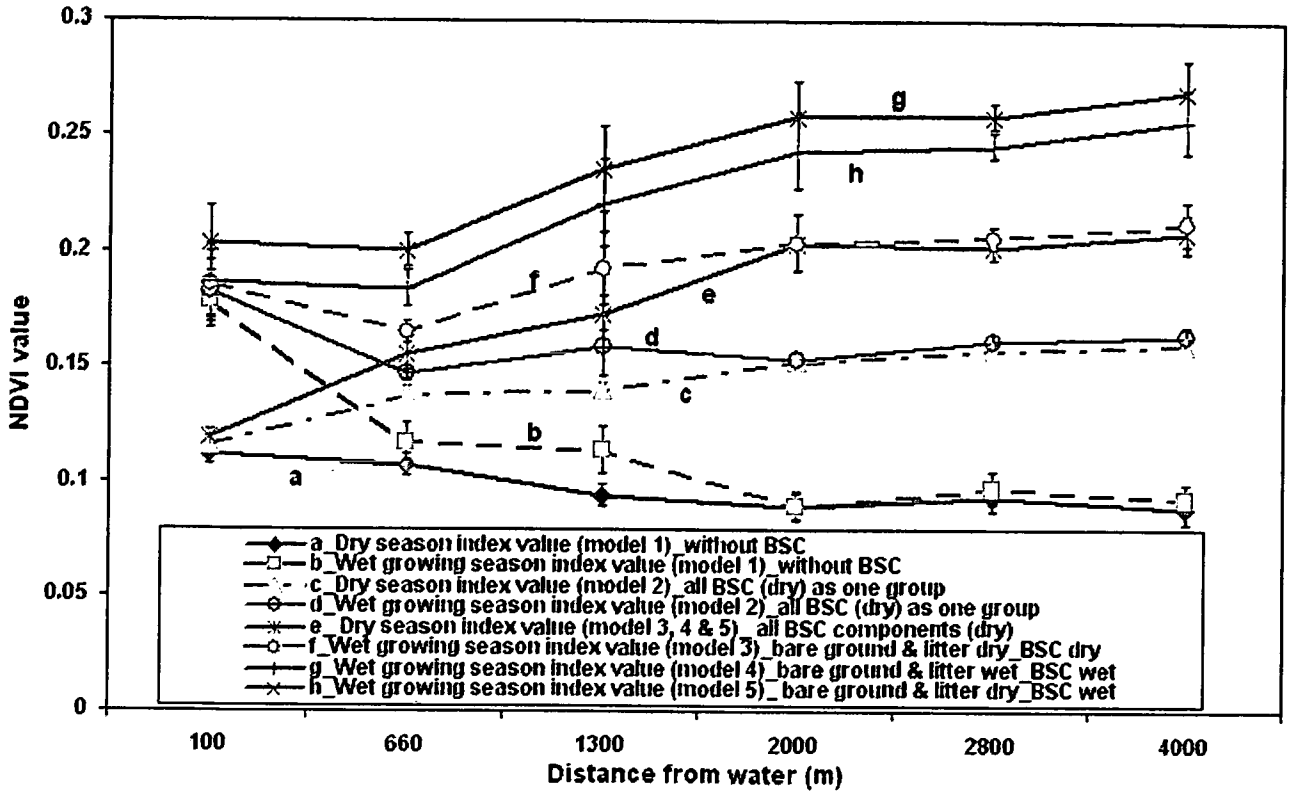

Figure 6-7. Mean NDVI value (± standard errors) as the mean of each site in five paddocks for modelling of dry *vs.* wet conditions for grazing gradient models at MFC

The second model (**c** & **d**) was established according to the previous remotely-sensed studies where BSC were part of their studies (Lewis *et al.*, 2001). According to this model, the derived results are almost a "permanent normal gradient" (2-7) for dry season data and an "inverse gradient" (2-7) for the wet season. There is a high difference between the real cover value and estimated cover value using this model. The third model (**e** & **f**) was the result of taking all BSC groups into account for the grazing gradient model estimation by their dry spectral value. Results are different from the previous model with high cover value as a "normal gradient" (2-7) pattern. The fourth model (**e** & **g**) was established to determine the effects of moisture in the NDVI values. It shows the highest NDVI value (**g**/ wet growing season model) and gradient pattern among the five models. However, a part of this high value is related to the moisture of soil and litter. General patterns of these models are a "normal gradient" (2-7). The fifth model (**e** & **h**) was derived from the wet NDVI value of BSC in comparison with the third model, which were based on the dry value. General patterns of these models are also a "normal gradient" (2-7).

6-5-3-2. Soil Stability Index

Figure 6-8 shows five-weighted SSI-based grazing gradient models for the collected spectra and ground cover data. General patterns of the models are almost the same as the derived models by the NDVI, particularly for model 1 **(a & b)**, model 2 **(c & d)** and model 3 **(e & f)** with small differences between dry and wet conditions. The differences between dry to wet conditions for models 1 and 3 are very small. The main differences with the derived models from the NDVI are for the wet condition patterns, which are mixed with models 3, 4 and 5 and there are no distinguishable patterns between these three models. Nevertheless, the cover value differences for the model without BSC, BSC as one group, and BSC groups model, are considerably different. The results of modelling grazing gradient based on the SSI showed that it is not a reliable index for ground-level spectral analysis, which was based on the different land covers. An important result from the SSI is also the different cover value for models without BSC, BSC as one group and BSC groups, which considered from the grazing gradient pattern perspective, is "inverse" to "normal" grazing gradients (2-7) and could possibly lead to misinterpretation of the rangeland condition.

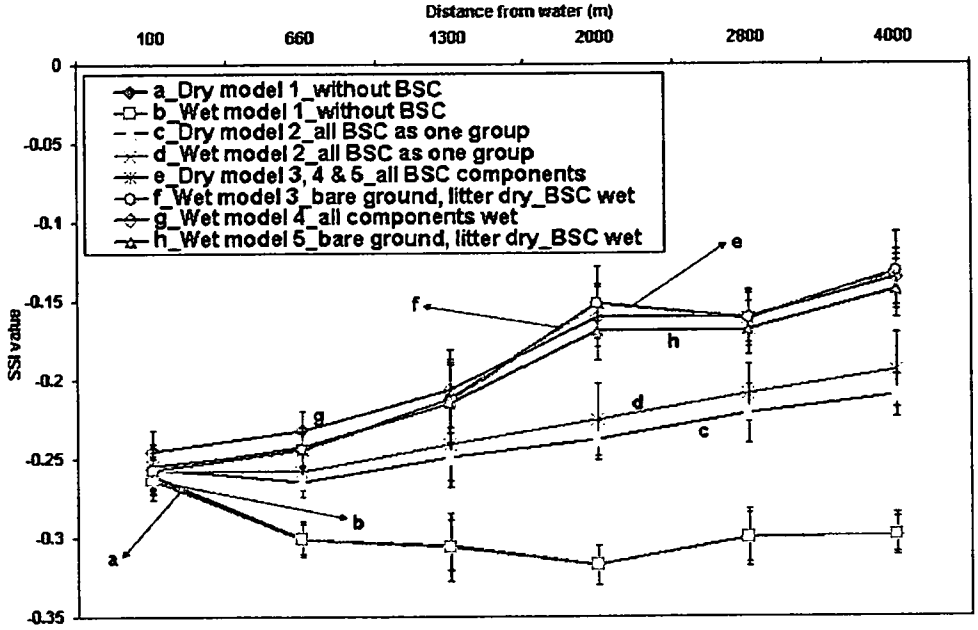

Figure 6-8. Mean weighted SSI value (± standard errors) as the mean of each site in five paddocks in modelling dry *vs.* wet conditions for grazing gradient models at MFC

6-5-4. Modeling Moisture Stability of Rangeland Covers

Results of previous sections show that there are distinguishable NDVI and SSI value differences between the dry and wet conditions for different models. In spite of the small differences from dry to wet conditions for land covers such as bare soil, litter and stone, there is the possibility of the effects of these on the overall results and misinterpretation in a remotely-sensed method.

Grazing gradient modelling showed that there is the possibility to define a scenario based on the dry bare soil, litter and stone, and wet BSC to detect these components (Model 5_**e-h**). The main concept in this scenario was based on the possibility of defining a period after rainfall that bare soil, litter and stone dehydrate but BSC can maintain their greenness value and if there is, after how many hours they will dehydrate. Alternatively, after how many days following rain would annuals start to grow and can we select remote sensing data to detect these subtle changes in rangeland state.

6-5-4-1. Laboratory Results

As can be seen from Figure 6-9, tall and short mosses have the highest NDVI value in dry and wet conditions. Moisture effects on Tall Mosses is very short and after a maximum of 2 days from wetting, the NDVI value returns to the dry spectral value, whereas in the short mosses it happens after nearly four days. Black Common Lichens, Scaly Lichens, Crusty Lichens and Leafy Lichens return to their dry values after 3 to 4, 4 to 5, 3 to 4, 4 to 5 and nearly 4 days after wetting respectively. In most of the BSC groups, the NDVI value reduction is sharp from wet to one day after wetting and then with a gradual decrease in the subsequent days. The pattern for Crusty Lichens (1.9% of total BSC cover) is discernable but NDVI values return to the dry conditions value after only one day. The NDVI value of BSC pattern, which is mostly representative of the black components, is almost the same as black BSC. Litter, stone and soil in the same situation have almost the same NDVI as dry conditions one day after wetting. [Although, according to the NDVI values test for stone, vascular plants and litter nearly 3 to 4 hours (maximum) after wetting their spectra change to the same spectra of dry conditions. However, for this study, it was assumed one day after wetting for drying of these components from the laboratory results.] Thus, according to the results of the laboratory data the second and third day after rainfall at 20 to 23°C is suitable for image selection for BSC detection.

Other considerable points from these results are: the NDVI values after 4 days are reduced for almost all components to lower than the dry conditions. As described in Section 5-4-5 species were stored outdoors under natural condition until the spectra collection. However, during the experiments, samples were kept nearly 4 to 6 hours in the "darkroom" and it seems there were significant effects of this situation on the Tall Mosses and spectral value change after wetting. Thus, from the photosynthetic perspective, this could be a possible effective factor in the overall spectral signature of different BSC components and needs more investigation. Moreover, the spectral variation of each group, as can be seen from the graph, "standard error bar" shows very high variations. This mostly arises from the merging of different species in the BSC groups or noise from the light fluctuations.

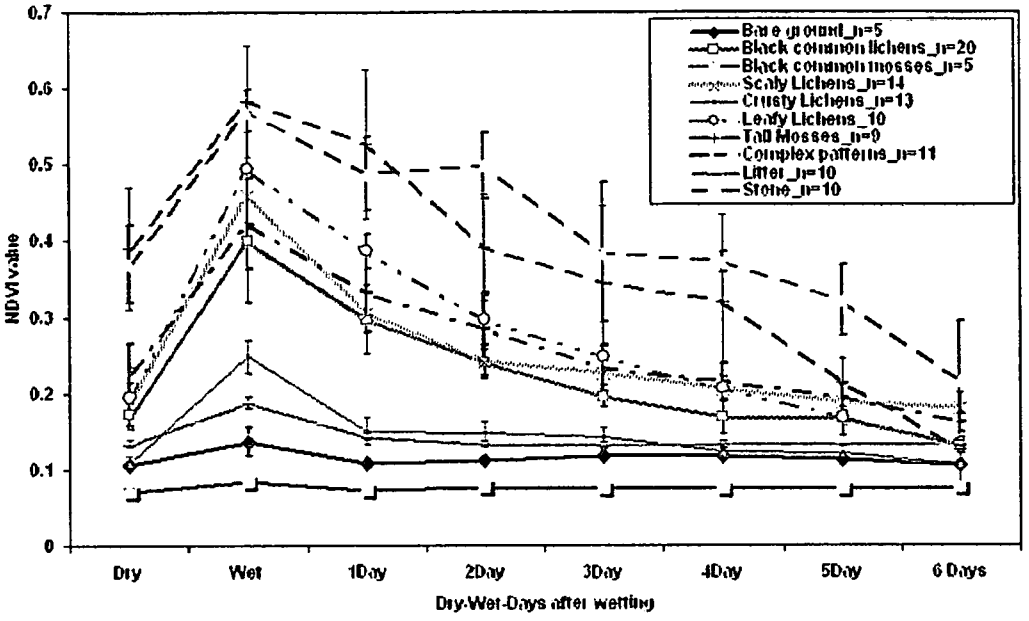

Figure 6-9. Mean NDVI value (± standard errors), after wetting for different land covers over time from wetting under the laboratory condition

6-5-4-2. Field Results

Summer-Spring Experiment

Low humidity and high temperatures had a strong influence on the moisture stability of all land covers. As can be seen from Figure 6-10, results are not supportive of the idea of detecting BSC in the hot period of a year (end of spring and summer time, with nearly 40°C / Appendices E-2 & F2). Although between the start of the experiment (2.30 pm) and collecting spectra the next day (11.00 am) was less than 24 hours, there were very low differences in the first day after wetting for all NDVI values between dry and wet conditions.

Autumn Experiment

Figure 6-11 shows the autumn experiment results. The results of this experiment can be classified as: Firstly, the effects of the amount of moisture on the stability of greenness, particularly in the second and third days. According to the results, 5 mm rainfall is not appropriate for image selection with the experiment time weather characteristics. However, rainfall greater than 10 mm can create the possibility of the image selection for detecting BSC after one or two days. Secondly, all of the NDVI values of bare soil, litter and stone spectra in the first day and after 5 to 6 hours of wetting, changed their spectra to the dry condition. However, the graph only presents the results of daily NDVI values. The spectral variation for bare soil, stone and litter with different amounts of moisture (5, 10, 15 & 20 mm) on the second day was similar or lower than the dry spectral value.

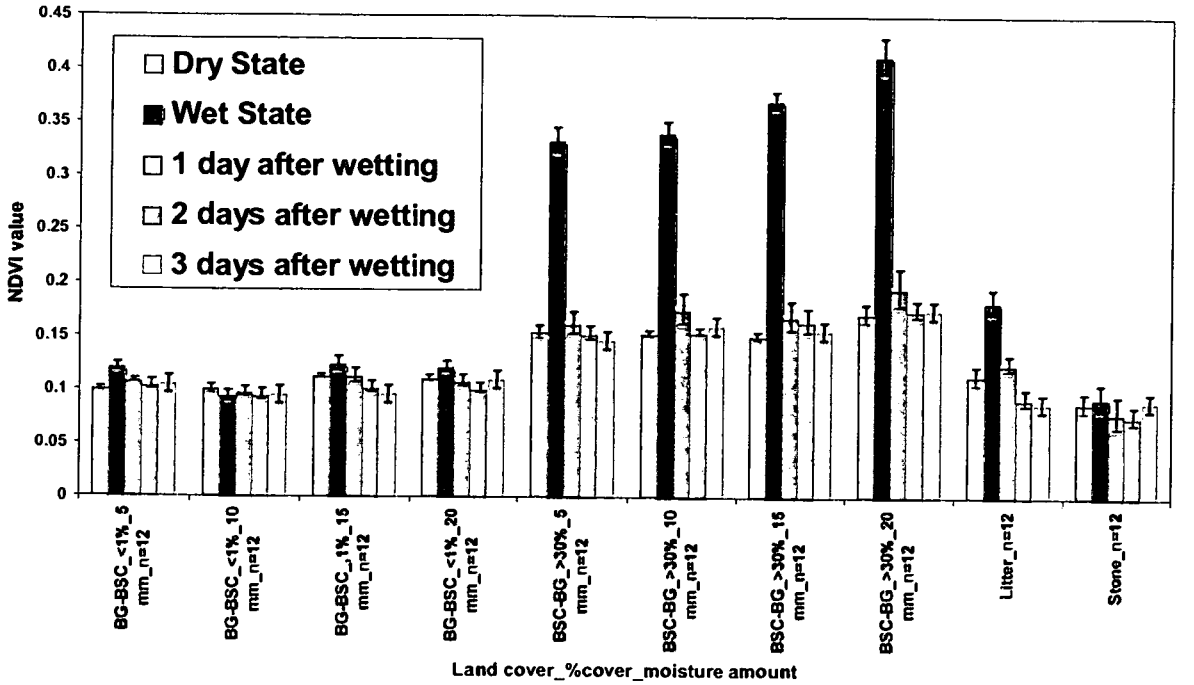

Figure 6-10. Mean NDVI value (± standard errors), after wetting for four bare soil samples (<1% BSC), four BSC samples (>30% BSC), litter and stone samples with the different amounts of moisture (5, 10, 15 & 20 mm) at MFC (spring-summer experiments / BG= Bare ground)

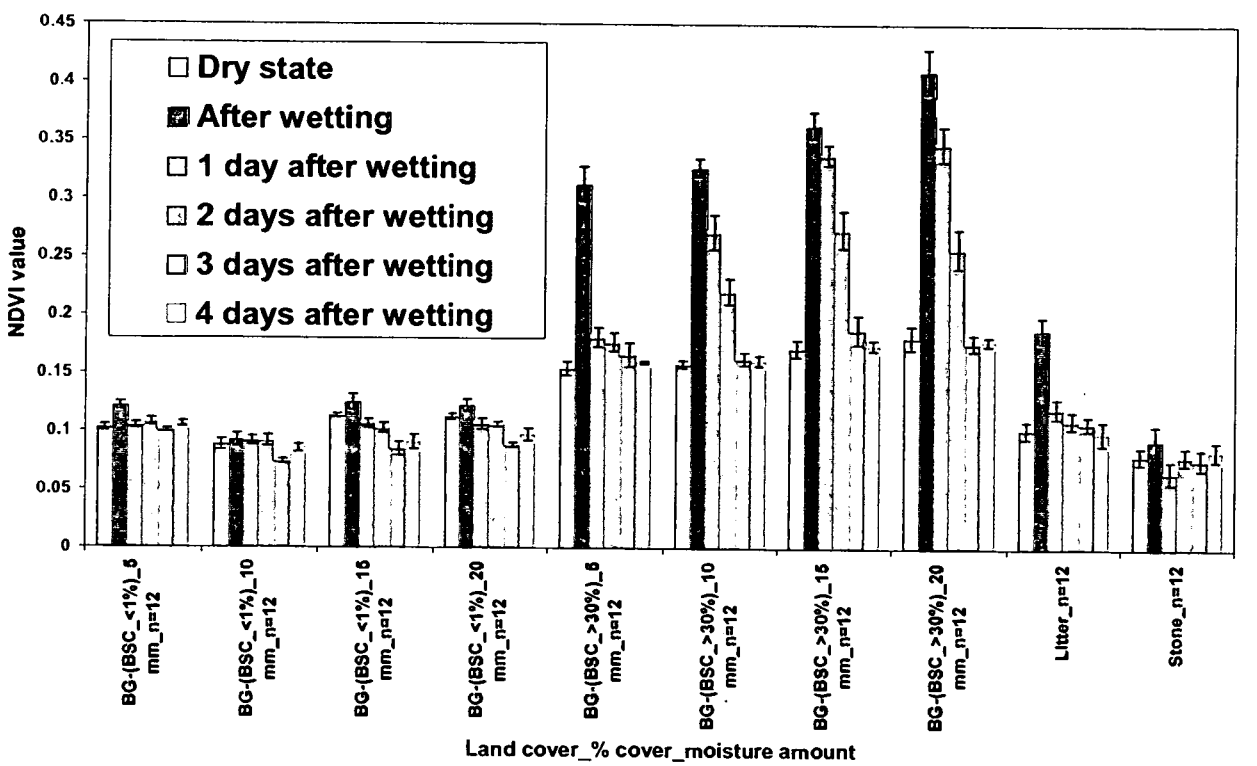

Figure 6-11. Mean NDVI value (± standard errors), after wetting for four bare soils (<1% BSC), four BSC covers (>30% BSC), litter and stone samples with the different amounts of moisture (5, 10, 15 & 20 mm) at MFC (autumn experiments / BG= Bare ground)

Thus there is no effect of soil, litter and stone moisture patterns on the second and third days after rainfall. Overall, results of this experiment show that there is a possibility of selecting remote sensing images for detecting BSC with the described weather pattern on the second day after at least 10 mm rainfall pulse, in the mid to late autumn, when annuals and perennials have not yet started to grow. As mentioned, summer and winter experiments were cancelled because of the spectrometer limitations.

6-6. Discussion

6-6-1. Comparison of the Differences and Similarities of Index Value between BSC in Dry and Wet Conditions

Index testing in the species and groups level in dry and wet conditions displayed considerable variations. The causes of spectral variations are discussed in Section 5-6-1. In the species level, index value variations are high with mixed patterns from species to species if compared with BSC groups. More importantly, the index value differences from dry to wet conditions for each species is considerably higher—particularly when compared with bare soil, litter and stone—thus it can create overall potential for remote sensing of these components when images are selected in their wet versus dry conditions. In the group levels for the NDVI and SSI, although the similarities between BSC groups are increased, the differences between dry to wet conditions is also considerably higher, supporting the idea of image selection based on dry versus wet conditions to detect the greenness value change when other biological elements such as annuals and perennials are inactive. See Chapter 7, for criteria used for image selection.

6-6-2. Comparison of the Differences and Similarities of Index Value between BSC *vs.* Other Land Covers in Dry and Wet Conditions

NDVI value similarities in dry and wet conditions for some of the BSC components with bare soil, litter, stone, shadow and vascular plant are considerable and support the results of studies in the Negev desert (Karnieli & Sarafis, 1996; Karnieli *et al.*, 1996; Karnieli *et al.*, 1999; Karnieli, 2003) allowing for the possibility of misinterpretation using this index between BSC groups and these components, particularly with bare soil. Misinterpretation could be more considerable if single image studies such as Lewis (2001) and Fildes (2005) are used for a remotely-sensed method in dry conditions of BSC. However, for the SSI, these similarities are very small, thus there would probably be a potential for using this index in dry or wet conditions in the area in which BSC are common.

The amount of index (NDVI or SSI) value change from dry to wet conditions for BSC components in comparison with bare soil, litter and stone is considerably higher. Thus, these

differences create a possible potential for image selection based on dry versus wet conditions for BSC detection when annual and perennial are not yet active. However, although the amount of index value change for bare soil, litter and stone in comparison with BSC is low, it can effect the overall results of a remotely-sensed method, thus caution should be exercised when conceptualizing it for BSC detection. See Sections 6-4-8 and 6-5-3 for moisture stability in this chapter (Model 5 scenario) and image selection in Chapter 7.

It should be noted that these are the results of individual BSC. There are differences between the individual spectra and overall spectra of a Landsat-like pixels, which is covered by many components. However, individual spectra showed dry spectra (index value) of BSC varying considerably, and they could affect the multispectral data that was to be used to separate natural variation from livestock pressure and degradation. Each individual spectrum may have small effects on the overall spectra of a multispectral pixels, but their variations could be an important source of effects on hyperspectral and high spatial remote sensing.

6-6-3. Examination of the Effects of Background Soil on the Overall Spectra and Value of Index in Dry and Wet Conditions

Results of this study for pattern analyses showed that differences exist between the NDVI values derived from single BSC with the spectra of a BSC community with bare soil background. These results support the view expressed widely in the literature that arid environments background soil brightness is one of the main problems for employing remotely-sensed data for biophysical components detection (2-8-4). My results show that very small NDVI value differences exist between the area covered with BSC in comparison with the area without BSC in dry conditions, and support the Negev desert results (Karnieli & Sarafis, 1996; Karnieli *et al.*, 1996; Karnieli *et al.*, 1999) that emphasized these similarities in dry conditions. Thus, there is the high possibility of misinterpretation of BSC as bare soil and vice versa in dry conditions. It should be noted that almost all of the previous studies, which were conducted on the areas in which BSC occur for avoiding moisture content, have selected their imagery in dry conditions (Cameron, 1995; Lewis, 1998; Lewis, 2000; Lewis *et al.*, 2001; Lewis, 2002b; Fildes, 2005). By contrast, in wet conditions, the differences between bare soil and BSC pattern spectra is very large and support O'Neill's (1994b) and others' (Karnieli *et al.*, 1999; Karnieli, 2003) studies that there are different spectral values in wet conditions, even with bare soil background. Thus, there is the possibility of BSC detection in pattern context in wet conditions, however the level of moisture is an issue and should be investigated for the possibility of BSC detection.

6-6-4. Effects of Index Value Similarity for Different Land Covers in the Interpretation of Remote Sensing Data

The index-based remotely-sensed methods such as the NDVI, SSI and PD54 have mainly been based on the spectral value differences in dry versus wet years for change detection in rangeland ecosystems (Bastin *et al.*, 1993a; Pickup *et al.*, 1993; Pickup *et al.*, 1994; Pickup & Chewings, 1994; Cameron & Lewis, 1996; Lewis, 1998). In these types of studies, both images were selected based upon the dry conditions of BSC. BSC can cover from 0 to 100% of the rangeland surface (West, 1990; Belnap, 1993). In remotely-sensed methods they have been less considered (McGregor & Lewis, 1996; Grierson & Lewis, 1998; Grierson *et al.*, 1998; Lewis, 1998; Lewis, 2000). In a few studies all BSC have been considered as one or at maximum two groups (Lewis *et al.*, 2001; Fildes, 2005). In the case of the area such as those at MFC which is characterized by winter-dominated rainfall (Rogers, 1982) and lichen dominance (3-10), the influence of different BSC on a remotely-sensed method should seriously be considered as an effective factor on the derived results from ground-based cover estimation (Ch.4). If BSC spectra are the same as bare soil spectra, the derived difference values from the NDVI are related to the vascular plant change in both images from dry to wet years. That is BSC cover is neglected or equated to bare soil. From the results of Chapter 4, BSC cover ranged from 1.69% at 100 m from water points to 36.99% at 4000 m, thus a given remotely-sensed data such as the study by Cameron and Lewis (1996) employed methods interpreting the equal spectral values for BSC and bare soil. This means 36.99% of BSC cover is equated as 1.69% by neglecting their advantages. Bare ground is equal to loss in soil potential productivity in response to a rainfall pulse as described by many studies (Tongway & Smith, 1989; Tongway, 1994, 1995b). Thus, if BSC are equated as bare ground in a given study, this can create biased results in the determination of rangeland conditions. Similarly, degraded areas are equated with undegraded areas.

6-6-5. Effects of BSC Cover on the Pattern (Model) of Grazing Gradient

The main question in this chapter was what the effects of BSC cover are on the pattern of grazing gradient? The ground-based data (4-5-1 & 4-5-2) and results of this chapter clearly defined the importance of BSC as a part of land cover in identifying grazing gradient patterns (2-7). Results of this chapter showed that distinguishable differences exist for the grazing gradient models without BSC versus including them as one group. My results showed that if image interpretation such as that of Lewis's (1998) study does not take BSC into account during cover estimation, then misinterpretation and bias could result. Moreover, my results showed that there are distinguishable differences between the models derived from BSC as one group versus models which used BSC groups. My results showed that single group selection, such as those of

Lewis *et al.*'s (2001) study who selected all BSC as one endmember, will create biased results in the cover estimation as lower cover value for a study area. The problem with a single group model could be more distinguishable if grazing gradient patterns were considered as "normal", "composite" or "inverse" (2-7), thus, there is the possibility of misinterpretation of rangeland condition using different models of BSC. More importantly, if interpreters use the estimated cover for a secondary analysis such as soil erosion estimation the results by using different models of BSC could be completely different.

6-6-6. Moisture Stability and the Possibility of the Selection of an Image for BSC Detection

In model 5 it was concluded that a conditional situation exists for BSC detection. The selection of an image for BSC detection was based on the dry soil, litter, stone and wet BSC when annual and perennial plants have not yet started to grow. Karnieli (2003) in Israel has also concluded an image selection based on the BSC growth stage when annual and perennial plants have not yet started to grow to use remote sensing data. However, the main controversial issue for this model could be the moisture stability for bare soil, litter and stone in comparison with BSC. In this study, there was no chance to complete all of the designed experiments for moisture stability in the natural condition. However, by considering the limited field and laboratory experiments conceptually there is a possibility of selecting an image in late autumn (May to early June) in the second or third days after an influential rainfall pulse to obtain the greenness values of BSC. Autumn experiments were conducted in 30°C, thus rationally there is an expectation that in the period with maximum 20°C temperature, the continuity of greenness for BSC, and higher moisture level for bare soil, litter and stone increases. Alternatively, if an image is selected in late August or early September after 2 to 4 days of a rainfall pulse, BSC greenness value will be included in the overall cover value. The results are not completely clear and need further investigation in the field on a monthly base with spectra collection to model the real extent of the period of dehydration for bare soil, litter, stone and BSC. Reviewed literature in Israel mostly compared dry spectra versus wet BSC spectra. Thus, with limited information about the soil, stone, litter and BSC moisture stability after a rainfall pulse in different seasons and different conditions, it is difficult to conclude the real extent of moisture stability in mentioned components. Karnieli (2003) reported that the beginning of the wet season is suitable for BSC detection, however, he did not cover the duration or moisture stability and biological activities of BSC after a rainfall pulse and did not compare this for other rangeland covers. Overall, more investigations are required in this regard.

6-7. Conclusions

There are different index values for BSC and other land covers in dry versus wet conditions. The amount of change, particularly for the NDVI for BSC, is larger than the bare soil, litter and stone. Similarities exist between index values of bare soil, litter and stone with dry lichens, particularly black BSC for the NDVI. Moreover, the index value of "BSC pattern" versus bare soil in dry conditions is similar to the wet conditions. Thus, there is potential misinterpretation in the results of image processing. BSC are important components in dry and wet conditions for deriving grazing gradient patterns. BSC cover broad groups of organisms, with different spectral values. Thus, different grazing gradient patterns and cover values exist derived from one collective BSC group versus a grazing gradient pattern derived from individual BSC groups. There is a considerable effect of moisture on the grazing gradient pattern. In comparison the wet model has the highest value (grazing gradient pattern) among the employed models. There are distinguishable grazing gradient patterns based on BSC detection using wet spectra of BSC and spectra of dry state of bare soil, litter and stone. However, it depends on the moisture stability of different land covers. Moisture stability is crucial for the use of remotely-sensed data to detect BSC. All rangeland covers, after a rainfall pulse, will be affected by moisture. Litter and stone dehydrate over a short period in comparison with soil and BSC. Bare soil in comparison with BSC has a shorter period for dehydration. Dehydration for each component depends on temperature, moisture and humidity. In the spring-summer, with high temperatures of about 35-40°C, all land covers dehydrate in one day. It is almost impossible to select an image based on this period to detect BSC. However, in the early spring, late autumn and winter the possibility of image selection will increase to 2 to 4 days after an influential rainfall (>10 mm).

CHAPTER 7

7. REMOTE SENSING OF BIOLOGICAL SOIL CRUSTS

This Chapter

Following the results of stratification (Ch.3), BSC cover variance analysis (Ch.4), spectral characterization (Ch.5) and ground-level spectral modelling (Ch.6), this chapter focuses on image-based data to examine the possibility of detecting BSC by remote sensing. To clarify the level of this study, it should be understood that this is not a stand alone remotely-sensed method, in that, this is not a kind of remotely-sensed method with image selection, pre image processing, image processing and random site selection for accuracy assessment and validation of the results on the spatial pattern. This study was based on index-testing and development using predefined sites from ground-based methods. Visual interpretation and digital analysis of remotely-sensed data only relied on the comparison and validation of the collected data by pixel values on the pre-defined sites, rather than a spatial pattern analysis and mapping of BSC. Thus, the presented results are for the tested indices and derived indices on the predefined sites. The application of the developed indices could be the next step of this study for BSC detection as a standalone remotely-sensed method with image interpretation and accuracy assessment in other BSC dominated areas. In this chapter, all of the analyses were based on the total BSC cover (because of the volume of the thesis) rather than each BSC group.

7-1. Introduction

The capability of remote sensing to detect and map the distribution of different land covers presents the opportunity to extend site-specific ecological surveys of those land covers to a regional scale, thus reducing the time and cost associated with ground-based studies. However, the mixture of spectra of materials such as different vascular plants, bare soil, litter, rock and different BSC within individual pixels can complicate the analysis of multi and hyperspectral data, often masking the diagnostic spectral features of materials of interest and obscurating their classification (Huete & Jackson, 1988; Bechtel *et al.*, 2002). A common example of this problem in arid and semi-arid regions is the ubiquitous presence of BSC covering exposed bare ground, and when mixed with vascular plants this may compromise the ability to map the reflectance signatures of minerals in dry seasons and vascular plants in non-dry seasons with multi and hyperspectral remote sensing (Karnieli *et al.*, 2001). Considering the global extent of BSC and expanding interest in their ecological roles, there have been relatively few studies conducted to detect and map their distribution (Wessels & van Vuuren, 1986; Karnieli, 1997; Chen *et al.*, 2005).

7-2. Cover and Remotely-sensed Methods

Cover has been used from spatial and temporal perspectives in remotely-sensed methods to determine land cover change and land degradation assessment (Bastin *et al.*, 1993a; Pickup *et al.*, 1994). These methods usually tried to measure the amount of vascular plant cover on the landscape by considering spatial distribution. Alternatively, a given method tried to measure variation in different stages of growth, in wet and dry years (Bastin *et al.*, 1993a; Pickup *et al.*, 1994; Okin *et al.*, 2001a). See Chapter 2 for details of cover indicator and remote sensing technology.

Examination of previous literature shows that a holistic view of BSC cover index from piosphere patterns using remote sensing has not been a part of former studies. A few studies have been conducted to discriminate BSC cover characteristics using image data analysis (Bork *et al.*, 1998; Bork *et al.*, 1999; Lewis *et al.*, 2001; Fildes, 2005). According to ground-based studies, there are considerable variations (between 0 – 100%) in BSC cover in rangeland ecosystems such as those in USA, China and Australia (West, 1990; Belnap, 1993; O'Neill, 1994a; Chen *et al.*, 2005) and from 1.69 to 36.99% in this study (4-5-3). Most of the remotely-sensed methods were conducted with little consideration of BSC (Grierson, 1998; Grierson & Lewis, 1998; Grierson *et al.*, 1998; Lewis, 1998; Lewis, 2000). In other studies, for example in Cameron and Lewis (1996), any mention of BSC is usually confined to broad classes of organisms i.e. cryptogamic, mosses or lichens, or used only in passing reference. This may relate to the difficulties of BSC monitoring at the species level (3-10) or disagreements about the importance of cover of these components (1-1, 1-13 & 2-6-2).

The question is if BSC are alive, if they have chlorophyll and ability to absorb water (6-2-2 & 6-5-4) and if they have different spectral signatures (Ch.5), how did previous studies classify their results without consideration of BSC, or consideration of them as one or two groups (Grierson, 1998; Grierson & Lewis, 1998; Grierson *et al.*, 1998; Lewis, 1998; Lewis, 2000). For example, Lewis *et al.* (2001), employed a mixture analysis techniques with a single time image, relatively dry mid-winter imagery (BSC in dry condition), selected BSC as one endmember in discriminating arid vegetation with the use of hyperspectral imagery. In another example, Fildes (2005), conducted a study for mapping landscape compositions using HyMap imagery in South Australia, on an area where BSC are common. He has also used a spectral mixture model and selected lichens as two endmembers.

As described in Section 1-15, there are other studies which were undertaken for BSC mapping using remotely-sensed data. For example, Wessels and Van Vuuren (1986) were the first to

use remote sensing data to map BSC. They used Landsat TM data to map lichen-dominated areas in the Namib Desert of Africa. Karnieli (1997) has developed an index based on field spectrometry, colour aerial photography and TM imagery to detect cyanobacteria- dominated areas in the Negev desert. Karnieli (2003) has proposed image selection based on the phenological states of BSC, annual and perennial elements. He used ground-level spectral analysis in cyanobacteria-dominated rangelands to develop this methodology in the Negev desert. Finally, Chen *et al.* (2005) attempted to map lichen-dominated rangelands by developing a new index, which was based on the Landsat ETM+ imagery in China.

7-3. Aim of Chapter

Pickup *et al.* (1993) stated that, "...in Australia's arid rangelands, the amount of vegetation cover is a major determinant of the quantity of fodder available for grazing, the risk of erosion, and the fuel load in bushfire hazard situations". They also stated that "...estimating cover or cover change quickly, cheaply, and cover of large areas is, therefore, a key problem if remote sensing techniques are to be applied to rangeland monitoring". BSC are common in the larger parts of Australian's rangeland (Figure 2-2). They are important because of their effect on soil stability and other ecological roles (Chs. 1, 2, 3 & 4). Moreover, as discussed in Chapters 5 and 6 BSC can effect the spectral signature of other land covers such as bare soil and vascular plants and lead to overall misinterpretation in a remotely-sensed method. A remotely-sensed method applied to an area in which BSC are common has to take BSC into consideration when interpreting images. There is limited understanding and hence detection of these components using remotely-sensed methods, particularly in Australia. Thus, this chapter aims to:

1. Investigate the effects of BSC on the multispectral dataset such as Landsat TM for cover estimation by testing different indices and graphical analysis, and
2. Investigate the possibility of detecting BSC as one of the important land covers by deriving a new index using multispectral remote sensing.

7-4. Methods

The methodology utilized in this chapter was conducted in three steps: firstly, general spatial data management and preparation; secondly, determining a suite of procedures for image(s) selection;

thirdly, considering the dataset capability to develop a suite of procedures to find the effects of BSC on the image data and a possible index for detecting BSC.

7-4-1. General Aspects of Remote Sensing and GIS Methods

7-4-1-1. Spatial Dataset and GIS Layers

Base spatial data used in this thesis are described in Section 1-16. Moreover, some GIS processing such as construction of a DEM and slope maps (3-2-2) and zonal-based operations in this chapter were carried out using the ArcView (ESRI, 2002), ArcGIS (ESRI, 2004) and ERDAS Imagine (Leica Geosystems, 2004b).

7-4-1-2. Geometric Correction and Rectification

The earth is moving while a satellite image is being captured and the Instantaneous Field Of View covers more territory at the ends of scan lines (where the angle of view is very oblique) than in the middle. Additionally, acquired images can be distorted by the curvature of the earth, relief displacement and the acquisition geometry of the satellites (i.e. variations in altitude, attitude and velocity) (Lillesand & Kiefer, 2000). Thus, there is a requirement for geometric correction of the acquired images even in seemingly flat areas such as those at MFC. The intent of geometric correction is to compensate for the distortions introduced by these factors so that the corrected image will have the geometric integrity of a map (Lillesand & Kiefer, 2000). With commercial satellite imagery, such as Landsat, SPOT and ASTER, most elements of geometric restoration associated with image capture e.g. skew correction and scanner distortion correction are corrected (systematic geocorrection) by the distributors of imagery (ACRES, 2004). This study was based on the first level of geometric correction by ACRES on the acquired images. Obtained imagery as mentioned in Section 1-16 has been registered to the UTM map projection with a datum of the GDA 94 by ACRES. However, according to the collected Ground Control Points (GCP) and other GIS layers such as registered topographic maps, paddock boundaries and watering points, acquired images were still required to be rectified by the polynomial transformation model to the GDA 94 to align accurately with the GIS layers and collected GPS points. The study sites for this thesis (paddocks) are all located in one zone—Zone 53— with a central meridian of 137° east longitude. In image rectification Root Mean Square errors of 21 points selected from 50 GCP were less than 2 pixels and total Root Mean Square was 1.08 pixels.

7-4-1-3. Data Enhancement

Most image enhancement techniques are aimed at providing the analyst a better view of the data so that subtle features previously unnoticed by the analyst become more apparent. In the case of noisy data some filtering of that noise is necessary, preferably before proceeding to enhancement and interpretation. In this thesis, the main enhancement technique utilized was simply that of a histogram contrast modification. However, Principal Components Analysis (PCA) as a feature analysis was also utilized to determine the high and low correlation between spectral bands for index analysis of TM imagery. See Sections 7-4-5 & 7-5-1 for details of PCA.

7-4-1-4. Interpretation of Remotely-sensed Data

Remotely-sensed data interpretation was considered in two sections as: visual interpretation (3-5) and digital analyses (this chapter). Visual interpretation was considered as image enhancement, contrast stretches, band combinations for interpretation of features on the basis of tone, texture, colour pattern and distribution for resource stratification. Digital interpretation was considered for individual landscape covers as band ratios (indices).

7-4-2. Criteria for Image Selection

7-4-2-1. Climate / Weather Criteria

As presented in Section 3-2-1 and Appendix E-8, there are variations for the number of rainy days at the MFC, Roopena, Iron Knob and Whyalla stations. However, these variations are mostly related to the small rainfall events and rainfall regime differences between the Whyalla and other stations. According to the proximity to the sea, rainfall (amount and frequency) in the Whyalla station is higher than the MFC. Moreover, as mentioned in Section 3-2-1, the MFC rainfall events of less than 1 mm were not recorded. According to Figure 3-2 and Appendix E-8 in 2003, there were 88 rainfall events recorded in the Whyalla station versus 47, 41 and 37 events in the Roopena, Iron Knob and MFC respectively. It should be noted that in Roopena and Iron Knob all rainfall events were recorded, so the number of rainy day differences is related to rainfall regime differences. In 2004 the number of rainy days in the Whyalla station was 95, Roopena 47, Iron Knob 45 and at the MFC 32 events. All BSC respond to moisture immediately after a small amount of moisture (Karnieli *et al.*, 1999; Karnieli, 2003), however, it was assumed that a suitable rainfall to detect greenness value of BSC was at least 4 to 5 mm. For this amount of rainfall, the MFC dataset, which had the lowest number of rainy days and closest to the study paddocks was utilized. MFC had 20 rainfall events more than 4 to 5 mm in 2003 and 19 events more than 4 to 5 mm in 2004. However, from the results

of the moisture stability experiment in Chapter 6, in late spring and autumn a rainfall event of significance was determined to be at least 10 mm. Thus, regarding these limitations, the number of influenced rainfall events was reduced to 10 in 2003 and 7 in 2004. Overall, during the almost two years, there was the possibility of selecting 17 images to analyze the effects of BSC.

Another consideration from climatic and atmospheric perspectives was: to minimize the effects of seasonal variations such as changes in the illumination levels and solar elevations that affect the amount of shadowing present within an image it is best to select images in the same season. However, regarding the phenological stages of annual, perennial and BSC the selection of images in different seasons of a year was inevitable. Cloud also plays an important role at the time of image selection. As Graetz and Gentle (1982) reported, imagery with cloud cover greater than 20% is useless for vegetation cover estimation. Clouds are highly reflective and tend to mask the presence of vegetation or bare ground underneath (Graetz & Gentle, 1982). In the image selection stages, attempts were made to avoid selection of cloudy images.

7-4-2-2. Moisture Criteria

Surface soil moisture content, which can change reflectance in multispectral remote sensing data, is usually a very short-lived feature in Australia's rangelands (Pickup *et al.*, 1993). Moisture effects in previous studies were considered by selecting imagery nearly 4 to 6 weeks after rainfall events (Bastin *et al.*, 1993a). This period was considered not only for avoiding moisture content, but also for obtaining the highest greenness or cover value. Moisture content was crucial for this study, because of the selection of image(s) very close to the rainfall events. As described in Chapters 5 and 6, this issue was considered in advance by spectral characterization and ground-level spectral modelling. Spectral characteristics for a synthesized TM imagery was considered by examining the data space of each BSC group in dry and wet conditions in comparison with other land covers (Ch.5). The second consideration to define moisture effects was the result of moisture stability (dehydration) experiments for different land covers undertaken in Chapter 6, although the planned experiment for the moisture stability was not completed. The results of two experiments have shown a very short period for desiccation of litter, stone and bare soil at less than 1 day (6-5-4). Furthermore, from the results of spectral analysis for different indices in dry versus wet conditions of different objects, bare soil had very small variation (6-5-1 & 6-5-2).

7-4-2-3. Biotic Elements Criteria

Phenology of three biotic elements including BSC, annuals and perennials were considered in the development of a remotely-sensed method for detecting BSC. Precise modelling of a region's phenology is difficult and perhaps impossible with the knowledge and technology available to researchers today. However, some variables such as accumulated rainfall, magnitude and size of events (3-2-1 & Appendix E) are believed to agree well with phenological events, and can be used as estimates or correlates of phenology (French & Sauer, 1974; Weber, 2001). Hence, pheno-phases (physiological stage of development) of the BSC, annuals and perennials to derive growing stages for the study year were considered.

BSC

Pheno-phases of the major BSC groups including: Black Common Lichens, Black Common Mosses, Crusty Lichens, Scaly Lichens, Leafy Lichens and Tall Mosses were considered in two steps. Firstly, phenological observations of these groups in a monthly-based field control in 19 field visits during the study (Appendix E-2). For BSC phenological records the beginning of the growth (after how much time BSC responded to moisture) and the end of growth (after how much time BSC dehydrated) were recorded. During the study (Appendices E-2, E-6 & F-2), only 9 out of 19 field visits were synchronized with rainfall events and the active mode of them was recorded as 1 versus inactive mode as 0 (Table 7-1). After a rainfall event, stability of greenness for the different BSC groups was recorded. From the early field visits it was concluded that as some of the field visits were synchronized with dry conditions so there was no BSC activity to record. Therefore moisture stability experiments in the laboratory and field for spectral measurements were considered to simulate pheno-phase and spectral characteristics of BSC and other land covers for remote detection of BSC (6-5-4). In these experiments, artificial wetting was planned as 5, 10, 15 and 20 mm at four seasons, spring, summer, autumn and winter. Response of different BSC was recorded by measuring spectral value (6-5-4). In each period after wetting, spectra were collected each day and greenness appearances were recorded. As the spectrometer was not available, spectral measurements were taken only twice (6-5-4). Overall, pheno-phase patterns of these elements were used to derive general pheno-phase stages for BSC.

Pheno-phases of BSC between different groups are simple as active (in growth stage) versus dormant (no growth) (Table 7-1). They do not have a particular growing season and at any time of the year; if there is availability of moisture, after a few minutes, they will start to grow (Karnieli, 2003; Burgheimer *et al.*, 2006a). However, there are small differences between their greenness stability, particularly between mosses and lichens (6-5-4). Defined BSC groups were considered to

analyze these slight differences. The greenness period (stability of growth) depends on the season and amount of moisture, temperature, evaporation rate, humidity and other climatic factors. For example, in summer after 2 to 3 hours wetting (5, 10, 15 and 20 mm) all lichens dehydrate, but mosses can keep their greenness about 4 to 5 hours after wetting (6-5-4). In autumn and spring, this period can increase to 2 to 5 days after wetting or a rainfall pulse for mosses, but in lichen groups the period is nearly 1 to 4 days (the period depends to the climate /weather conditions). In winter, moss greenness after wetting or an effective rainfall can continue to 5 to 10 days and for lichens 3 to 7 days are estimated. Tall Mosses have a longer greenness period in comparison with short mosses. Among lichens and cyanobacteria groups, cyanobacteria, Scaly, Crusty and Leafy lichens have shorter periods of greenness in comparison with other Black Lichens. See Section 6-5-4 for details of moisture stability experiments.

Table 7-1. Phenological observations of different biotic elements during 28 months at MFC (1=activity or growth stage, 0 =no activity)

Biotic elements	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
	0*	1**	0	0	1	1	1	1	1	0	1	1
BSC	No specific season, it depends on the moisture contents in any season. If moisture is available, BSC are in a growth stage, if moisture is not available they are in a dormant mode. Moisture stability/active mode for BSC after a rainfall pulse in hot seasons is very short (less than one or maximum two days), however in cold seasons the growth activity can increase to more than 2 days, which is completely dependant on the climatic characteristics / See Chapter 6 for moisture stability experiments.											
*Maireana pyramidata***	0	0	0	0	0	0	1	1	1	1	0	0
*M. sedifolia****	0	0	0	0	0	0	1	1	1	1	0	0
*Atriplex vesicaria****	0	0	0	0	0	0	1	1	1	1	0	0
*Acacia spp.****	0	0	0	0	0	0	1	1	1	1	0	0
*Lycium australe****	0	0	0	0	0	1	1	1	1	1	0	0
Grasses***	0	0	0	0	0	0	1	1	1	1	0	0
Forbs***	0	0	0	0	0	0	1	1	1	1	0	0
Annuals (Forbs & Grasses)	0	0	0	0	0	1	1	1	1	0	0	0

* 0 for BSC does not mean there is not a constant phenological pattern in a given month for these components, it just representats no moisture during the field visit

** 1 for BSC does not mean there is a constant phenological pattern in a given month for these elements, it just represents moisture availability for growth of these components. It should be noted that presented data as active mode is related only to one observation during the study years (except June and August). For example, in Feb., Nov. and Dec. in the second year there was no evidence of BSC activity at the same time.

***Perennial plants

Although BSC respond to moisture at any time of the year, their pheno-phase characteristics (as active and inactive) were important for this study when annuals and perennials were not yet active. Another consideration was the image selection limitations for BSC detection in dry periods of the year. The response of BSC in dry periods to moisture with different amounts, which was less than one day (start of growth and then dehydration), caused difficulty of image selection for remotely-sensed methods during this period. Thus, a considerable growth period was early spring, winter and late autumn to differentiate between the growth of annual, perennial and BSC with at least 10 mm rainfall. As can be seen from Figure 7-1, if moisture is available, BSC are in the growing stage from early autumn when temperature trends became suitable for image selection until late October. It should be noted that the presented pattern in Figure 7-1 for BSC is completely dependent on the moisture availability, and for image selection based on BSC on this period/ pattern daily weather data should be considered. The greenness of BSC can be synchronized with annuals and perennials in the growing stage of these components, if moisture is available.

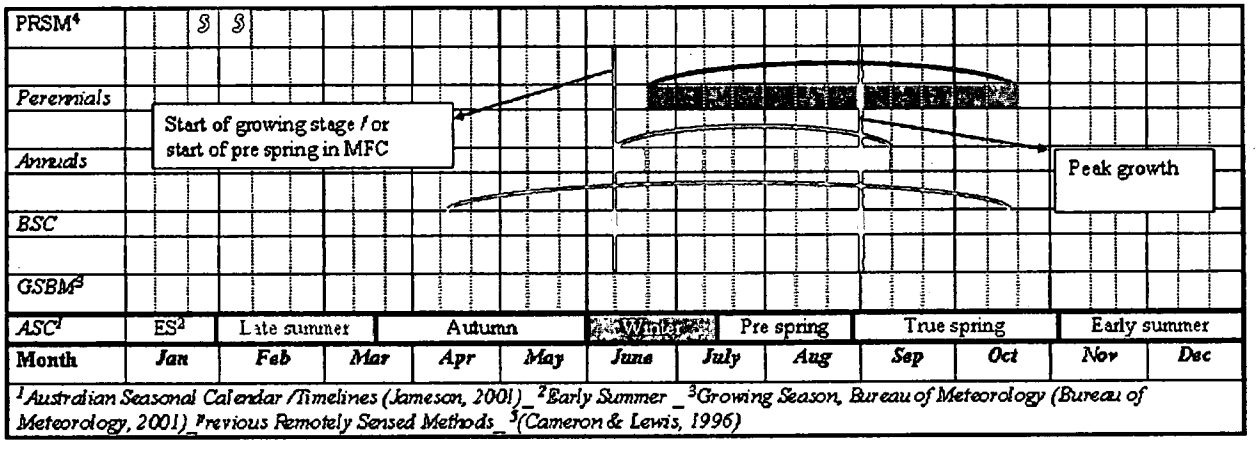

Figure 7-1. Phenological patterns of annuals, perennials and BSC in the context of Australian timelines (Appendix E), growing season for rainfall pattern between 140 mm to 267 mm and an example of selected imagery time from previous studies

Ephemeral Plants

Annuals including grasses and forbs were recorded in the field as appearance (germination), growth and development, and senescence stages. The study years had low rainfall for annual growth in summer time, particularly the year 2004 (3-2-1 and Appendix E). Although the amount of rainfall for late summer in 2003 was nearly 50 mm (non-continuous) with a 20 mm rainfall pulse in late summer in 2003 (Figures 3-2-1 and Appendix E), there was no evidence of summer growth. The effect of a 267 mm rainfall around the Whyalla station in 2003 was also considered, but there was

no summer growth for this amount of rainfall. In this year in the Whyalla region after 92 mm non consecutive rainfall for three months (Dec, Jun and Feb), there was no evidence of summer growth. More importantly, in this year, in February with 64.2 mm rainfall (in three days) there was no evidence of summer growth. Consequently, a much higher summer rainfall than 92 mm is required for the growth of ephemerals. Overall, according to the considerable rainfall in winter (more than 20 mm, nearly constant in three years), the early spring at MFC was started from late June initially by the growth of annuals, particularly annual forbs and then followed by annual grasses. Growth of annuals continues until late August to early September. From almost two years' observations (Appendix E-6) the colour of annuals started to change and turn to dry in early September. From the results of phenological observations the best time to obtain the highest percentage cover of annuals is about late August (Figure 7-1) for the study years.

Perennial Plants

For species such as *Maireana pyramidata, M. sedifolia, Atriplex vesicaria* and *Acacia* spp., pheno-phases including early growth (start of the growth for different species), peak growth (when most of the perennial plants were in the flowering stage and their vegetative growth stage was completed) and senescence (when the flowering was completely finished and there was no evidence of any growth) were recorded by monthly field visits (Appendix E-6). There are some requirements such as minimum moisture and temperature for the growth of perennial plants. According to the climatic data from late June to early July, moisture and temperature patterns at that time are most suitable for vascular plant growth. In this period, most of the vascular plants started to grow. There is some species variation: for example, vegetative growth for species such as *Lycium australe* (non-dominant species) is almost 10 days (estimated) earlier than the other species. Therefore, the vegetative growth in the early stages of the first perennial to respond was considered to define the beginning of the growth for perennial plants. The maximum growth stage was considered by the completion of the growth of leaves, and the end of flowering stages for perennial forb species.

In the early stages of the growing season, near the time of commencement of annual growth, with almost 20 to 30 days delay, a discernable pheno-phase can be seen in *Lycium australe.* In that stage, there is no evidence for the growth of other perennials. For perennials, the most distinguishable pheno-phase for all species can be considered to be the flowering stages. Although flowering generally takes place in late August for species such as *Senna artemisioides*, but *M. sedifolia* has a broad period of flowering from late July to late August, and flowering for species such as *Maireana pyramidata* is in late July to early August. Finally, some of the other species

flower in late September. It should be noted that for some species the flowering stage is not the same as the peak growth stage e.g. *Maireana sedifolia*. Overall as depicted in Figure 7-1, the peak growth stage for most of the species is estimated between late August and early September which is synchronised with the late peak stage of annuals. Thus, it is difficult to discriminate pheno-phase stages particularly at the beginning and ending of the growing season. The presented pattern for perennials (Figure 7-1) was derived by observing pheno-phase stages and overall patterns of those for different species as phenogram. This is the results of nearly two years' observations and for more reliable results needs at least 20 years' data to conclude the real extent of perennial growth patterns.

Phenogram of the Study Years

A review of existing information and results from this study are presented in Figure 7-1. Results are classified as the overall pattern of different groups and species for BSC, annuals and perennials. BSC can grow at any time of the year with a little moisture. However, growth stability of these elements is crucial being very short in summer or dry periods, and a considerable period in the cooler months of the year. Phenograms of these elements are depicted for the study years. Annuals and perennials, with the observations of growth of the first species and the end of growth by colour change, are derived from almost two year's data. For a comparison with existing information, the Australian seasonal calendar *(ASC)* for the growing season (Appendix E-5) (Jameson, 2001; Jones, 2002; Keatley & Fletcher, 2003); *GSBM* = growing season, by Bureau of Meteorology (2001) are also presented in Figure 7-1. Selected imagery for dry (1989/02/04) and wet (1993/01/30) periods (Cameron & Lewis, 1996) are also presented as an example (Figure 7-1). Cameron and Lewis (1996) claimed that there was the possibility of growth of vascular plants with 477 mm rainfall for the preceding (1992) year in summer time.

Overall, according to the climatic and phenological patterns, there is the possibility of the selection of three images based on the growth stages of each element to examine the effects and detection of these components by a remotely-sensed method. Thus, by considering phenological records; three phenological stages, for three image selections, were considered to examine the effects and detection of these components (Table 7-2).

7-4-2-4. Sensor Criteria

One of the important decisions in applying a remotely-sensed method is the selection of both a suitable sensor and suitable imagery, particularly in temporally-based studies (2-9). Image selection was based on the defined aims, biological elements and climatic / weather criteria by investigating

the Australian Centre for Remote Sensing (ACRES) for all possible multispectral passive images. Table 2-3 presents some of the possible sensors, which have been commonly used in rangeland monitoring, particularly in Australia. As reviewed in Section 2-8, previous rangeland monitoring studies have been conducted using multispectral datasets such as Landsat imagery. More recently, imaging from the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) sensor, particularly from the cost, spatial and temporal resolutions perspectives is of relevance (Table 2-3). For ASTER imagery, in addition to the ACRES site, the Earth Observing System Data Gateway (EDG) and the Japanese GDS system were also investigated for a suitable image in the defined periods of 2003 and 2004. However, these sites revealed that there were no suitable images. The main limitation occurred due to the inability to order imagery such as ASTER-based on the rainfall-based image selection for the study period. Moreover, other imagery such as SPOT was also considered, however according to the mentioned limitation there was no available data from ACRES sites. Hyperspectral and high spatial data such as HyMap, QuickBird or IKONOS because of the financial limitations were not considered (Table 2-3). However, Hyperion depending on the cost perspective (Table 2-3) could be a next step to continue the application of hyperspectral data for BSC classification.

Table 7-2. The summary of the image selection and phenological stages for three images (Based on the study years' data)

Images	Conditions
1. **Wet image** (Image of total photosynthetic components)	Based on the full growth of annuals, perennials and BSC in late August (late pre-spring)
2. **BSC image**	Before annuals and perennials start to grow, in winter with low temperature, low evaporation rate, high relative humidity, after a rainfall pulse (maximum 4 days) for BSC detection (e.g. in June)
3. **Dry season image** (Image of perennials)	In summer, when there is no evidence of BSC and annual growth. In the period of the permanent perennial greenness e.g. December, January or February.

From the available passive remotely-sensed data, Landsat TM 5 images were the best fit to the rainfall events and biotic elements. Although, there were some limitations for selection of other kinds of sensors, there was also support for the selection of TM imagery. See Section 2-8 for more details on Landsat Imagery.

This study has tried to select images from the same senor and if possible in the same year to reduce the effects of secondary factors such as climate and sensor variations. There were nearly 42 records of Landsat imagery for 2003 and 2004, with 33 images being cloud free at the study area.

The time of each record was compared with rainfall events. Finally, a late pre-spring image (2003/08/22) was selected as the "Wet Image", for total photosynthetic components 2 days after a 10 mm rainfall event (Figure 7-2). The second image (2004/06/05) was selected after 3 (1 mm) and 4 (15.5 mm) days rainfall events in the winter and termed the "BSC Image". Unfortunately, Corio paddock in this image was under cloud. Thus, in this image only 24 sites were used for image interpretation (Figure 7-3). The third image was selected in summer (2003/12/12), after 24 days of a 20.5 mm rainfall event. This was selected for perennials detection and labelled as the "Dry Season Image" (Figure 7-4). There was no distinguishable vascular plant growth after this amount of rainfall and all BSC were in a dry condition.

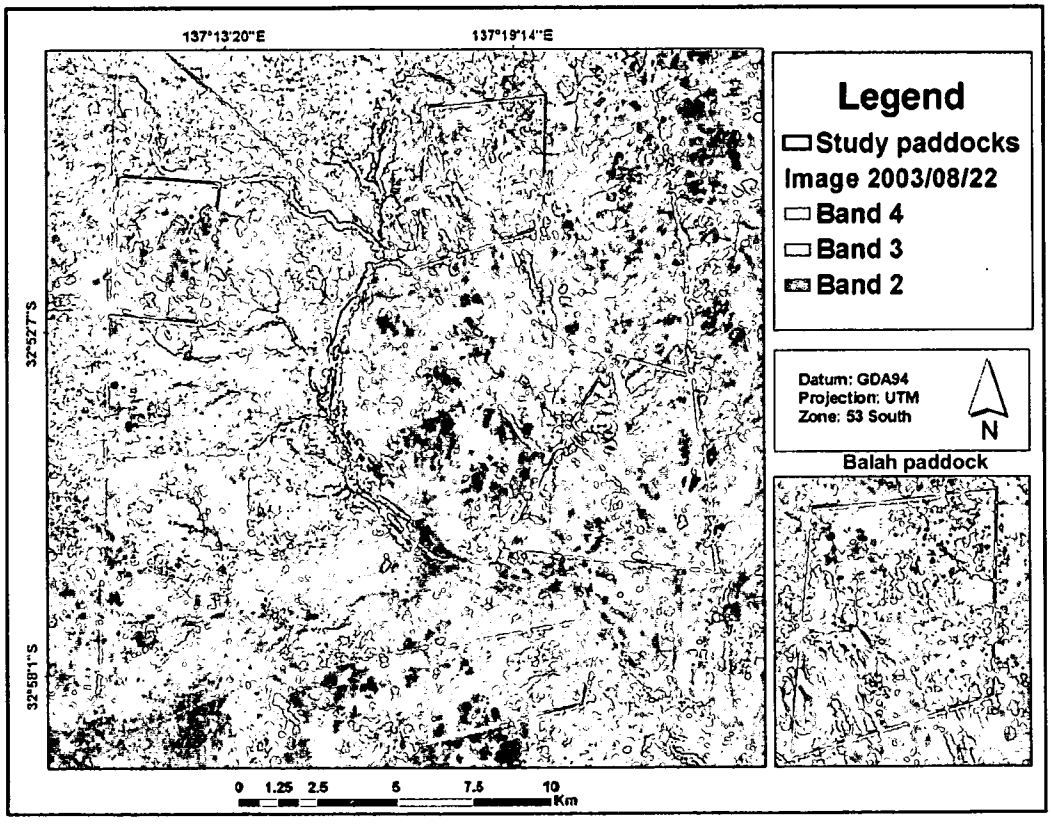

Figure 7-2. TM 5 "Wet image" in 2003/08/22 (2std Dev. Stretch enhancement) and study paddocks

7-4-3. Selected Images

To detect the effects of BSC in the context of phenological concepts three images of the TM 5 sub scenes (60 km × 60 km) of the MFC were acquired from ACRES. A summary of the image characteristics is presented in Table 7-3. Temporal imagery has been used to assist in discrimination of the MFC vascular plants and BSC, particularly by focusing on the scenes capturing the biological elements in different states. Moreover, another advantage of the TM imagery selection was the

similarity of the TM bands; 2 (green), 3 (red) and 4 (NIR) to the MSS bands and can be directly substituted for them (Crist & Cicone, 1984). It is important because most of the developed indices for rangeland monitoring in Australia were based on the MSS imagery (Pickup & Nelson, 1984; Bastin *et al.*, 1993a; Pickup *et al.*, 1994; Pickup & Chewings, 1994).

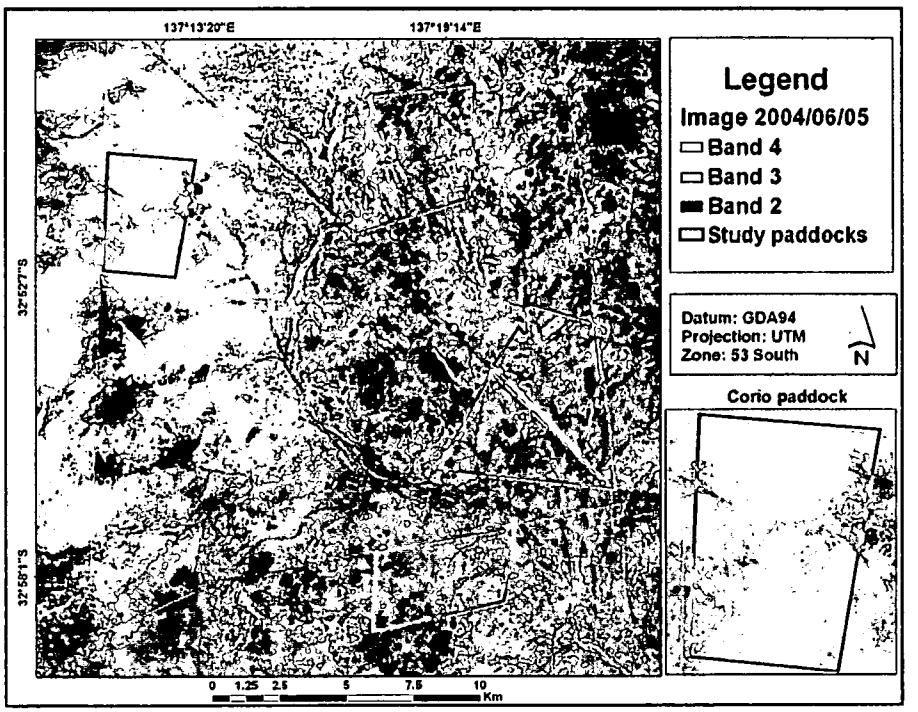

Figure 7-3. TM 5 "BSC image" in 2004/06/05 and study paddocks (for image analysis and index development cloud free area was used and Corio paddock was eliminated / presented image has contrast stretch of histogram specification)

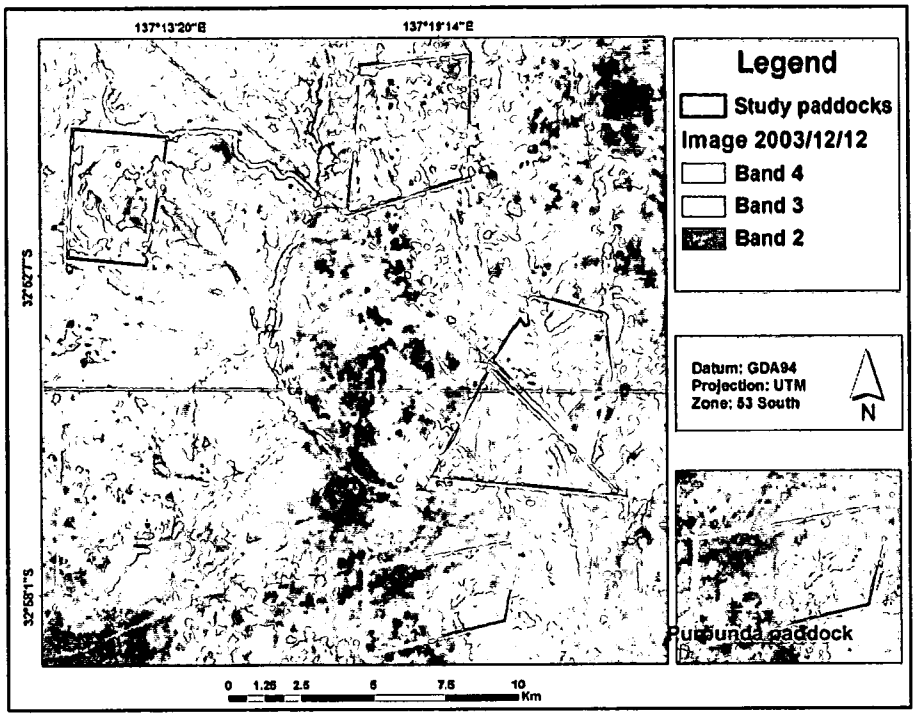

Figure 7-4. TM 5 "Dry season image" in 2003/12/12 (2std Dev. Stretch enhancement) and study paddocks

Table 7-3. The characteristics of the selected images

		Wet Image 2003/08/22 (Late pre-spring)	**Dry Image 2003/12/12** (Early summer)	**BSC Image 2004/06/05** (Winter)
Sensor characteristics				
Sensor type		TM 5	TM 5	TM 5
Satellite path /row		98/83	98/83	98/83
Sun elevation		31.76°	57.17°	24.88°
Sun azimuth		45.97°	81.96°	37.10°
Sun earth distance		1.01376	0.9878	1.01425
Spatial resolution: nominally is 30 m, but resampled to 25 m by ACRES done in the first level of image analysis				
Climatic characteristics for the image acquisition time [1]				
Average cloud for sub scene of study area (0-100%)		0	0	80% on the Corio paddock
Temperature (°C) (Whyalla station)	Max	19.5	26.7	16
	Min	4.8	13.4	2
Relative humidity (%) (Whyalla station)	9 am	99	81	99
	3 pm	37	30	43
Number of day(s) after rainfall until image acquisition in MFC		2 & 1[2]	24 & 6[3]	4, 3 & 2[4]
Amount of last rainfall in MFC (mm)		10	20.5	15.5
Total rainfall three months prior to image acquisition in the MFC (mm)		74.5	75.5	15.5 + 1[4]
Annual rainfall (mm) of proceeding year	MFC	118	118	221.5
	Roopena	125.5	125.5	202.4
	Iron Knob	124.1	124.1	205.2
	Whyalla	146.8	146.8	266.4
Biotic elements characteristics on the image acquisition time				
Annual growing stage		Active	Inactive	Inactive
Perennial growing stage		Active	Permanent growing stage	Permanent growing stage
BSC growing stage		Active	Inactive	Active

[1] Climatic components, after the last rainfall of each selected image are presented in Appendices G-2 to G-4.
[2] 2 days at MFC & 1 day at the Whyalla station
[3] 24 days at MFC, 6 days at the Whyalla station
[4] 15.5 mm rainfall 4 days before and 1 mm rainfall 3 days before the image acquisition date and 2 days before the image acquisition date at the Whyalla station

7-4-4. Image Pre-processing

As described by Campbell (2002) pre-processing refers to those operations that are preliminary to the main analysis. There are three main pre-processing stages: geometric correction (e.g. rectification and georectification); radiometric correction (i.e. radiometric and atmospheric correction), and feature extraction (e.g. principal components analysis). See Section 7-4-1 for rectification and georectifiction for this study.

7-4-4-1. Radiometric Correction

"...An important step in the development of methods for detecting, measuring and monitoring change through time in land condition is the ability to compare images from different dates and sites in different scenes" (Furby *et al.*, 1996). As described in Section 7-4-2, a temporal sequence of images throughout the different growing seasons and other time periods was acquired for this study. According to the selected images, radiometric correction was considered as an important stage for BSC detection. Previous studies have mostly selected a radiometric correction method and then started image processing. This study also aimed to use a simple radiometric correction model, but results for different invariant targets in the three images by employing a simple relative radiometric correction model (Furby *et al.*, 1996) were not reliable. Thus, a second procedure of radiometric correction was based on the collected reflectances of invariant target spectra and a third model was based on a simple sun standardization model. Finally, the best results were obtained by employing the COST model of Chavez (1996).

Radiometric Correction Based on the COST Model

For atmospheric and radiometric correction of TM imagery, the COST model of Chavez (1996) was used. The COST model is based on a simple but effective use of the dark object subtraction technique that accounts for both additive scattering and multiplicative transmittance effects (Chavez, 1996). COST uses the cosine of the solar zenith angle to approximate atmospheric transmittance and has been shown to be as accurate as models that use *in situ* (i.e., surface-based) atmospheric measurements and more rigorous radiative transfer code (Chavez, 1996). This model was developed using Spatial Modular Language for ERDAS Imagine by Skirvin (2000). The Skirvin ERDAS model (Skirvin, 2000) with modifications proposed by Chander and Markham (2003) for use with TM 5 dataset after May 2003, was utilized in this study. This model combines atmospheric correction and radiometric calibration (Chavez, 1996; Skirvin, 2000). Although some initial scene-dependent calculations must be performed to obtain necessary model constants, subsequent

processing of raw DN values to atmospherically corrected reflectances is performed in a single process. Images were radiometrically and atmospherically corrected using an Excel spreadsheet and ERDAS Imagine Spatial Modular to convert DN values to reflectance values.

For COST model calculation the solar elevation angle was obtained as "solar elevation angle (90°) minus solar zenith angle (θ)" for the date of image acquisition from the image header. The earth-sun distance "d" (in astronomical units) in an ephemeris for date of image acquisition was obtained from Table III in Chander and Markham (2003). Minimum DNs (brightness values) for each reflective band were obtained from band information. DN value was converted to an at-satellite minimum spectral radiance value according to the equation 7-1:

$$L_{\lambda,min} = LMIN_{\lambda} + QCAL * (LMAX_{\lambda} - LMIN_{\lambda}) / QCALMAX \qquad \text{equation 7-1}$$

where QCAL is minimum DN, QCALMAX = 255 and constants $LMIN_{\lambda}$, $LMAX_{\lambda}$ are given in Table I in Chander and Markham (2003). For each band, radiance of a dark object (assumed to have a reflectance of 1%) was computed by Chavez (1996) equation (Eq 7-2):

$$L_{\lambda,1\%} = 0.01 * ESUN_{\lambda} * COS^2 \theta / (\pi * d^2) \qquad \text{equation 7-2}$$

where $ESUN_{\lambda}$ = mean solar exoatmospheric spectral irradiance obtained from Table II of Chander and Markham (2003). Finally, haze correction was computed by Chavez (1996) equation (Eq 7-3)

$$L_{\lambda,haze} = L_{\lambda,min} - L_{\lambda,1\%} \qquad 7\text{-}3$$

The fundamental radiance to reflectance equation (Eq 7-4) of Chavez (1996) is:

$$\rho = \pi * d^2 * (Lsat_{\lambda} - Lhaze_{\lambda}) / ESUN_{\lambda} * COS^2 \theta \qquad \text{equation 7-4}$$

Alternatively, with more detail for a given band is:

$$\rho_{BandN} = \pi * d^2 * ((L_{BandN} * Gain_{BandN} + Bias_{BandN}) - (H_{BandN} * Gain_{BandN} + Bias_{BandN})) / E_{BandN} * (COS ((90- \theta)* \pi /180))* \tau \qquad \text{equation 7-5}$$

where, ρ_{BandN} = Reflectance for Band N, L_{BandN} = Digital number for Band N, H_{BandN} = Digital number representing dark object for Band N, d = Normalized Earth-Sun distance, E_{BandN} = Solar irradiance for band N and τ = Atmospheric transmittance expressed as (COS ((90- θ) * π /180))

After scene-specific components calculations, such as solar elevation angle, earth-sun distance "d" and also $L_{\lambda,haze}$ correction factors for each spectral band in each model for three images by the expression of the model was performed in the ERDAS Imagine Spatial Modeller. Deep sea water was used as the "dark object" for all images. See Appendices G-5 and G-6 for an example of detailed COST model calculations for "Wet image" 2003/08/22.

7-4-5. Image Processing for BSC Cover Detection

7-4-5-1. Preliminary Stage in Rangeland Monitoring Using Image Data

Landsat images were used to evaluate the effects of BSC to cover value change at different distances of watering points in dry and wet conditions. In addition to the usual mentioned pre-processing procedures for a remotely-sensed method, in rangeland monitoring there is an extra preliminary stage, which arises from the spatial heterogeneity of rangeland ecosystems. As stated by Pickup *et al.* (1993), "... a useful index must be capable of handling both spatial and temporal variability". On the rangeland, there are complex situations of vascular plants and soil colour, which can affect an index independently of the amount of cover present (Williamson, 1989; Pickup *et al.*, 1993). Pickup *et al.* (1993) and Brook *et al.* (2001) have reported that to overcome this problem it is necessary to stratify each satellite image on the basis of soil or vegetation type if a suitable land system or land unit map does not exist. As described in Section 3-5-3 there was no suitable stratified map for the study area, and this study was stratified using visual interpretation of each paddock for homogeneous sampling units.

7-4-5-2. General Concept and Procedure for BSC Cover Detection

The main concept was the evaluation of the impact caused by livestock concentrations on components of cover in different phenological conditions at different distances from water points by numerical (correlation coefficient) and graphical analysis. The image processing concept was a type of change detection. Changes related to the BSC percentage cover at different distances from water in wet and dry conditions, in comparison with perennial and annual percentage cover. Three images were selected based on three phenological stages (Table 7-3) to measure the magnitude of change of each element. Many approaches exist for change detection using remotely-sensed methods (Lu *et al.*, 2004). Those band combinations or indices for visible and NIR bands of TM imagery were mostly considered for this study. Beyond those, bands 5 and 7, despite the limitations of the ground-level spectral analysis, were also considered for new index development. For this purpose, some of the commonly used indices such as the Simple Ratio (SR), NDVI and SSI were utilized to examine the effects of BSC cover on the gradient patterns. Image derived gradient patterns for a given index were compared to field measured cover gradients to evaluate their significance for BSC monitoring. After band analysis and testing existing indices, different possible combinations of the TM bands were used to derive the best index or indices for BSC detection.

7-4-5-3. A Pilot Study

In the image processing stage, before the radiometric correction, "Raw Images" (acquired images from ACRES) were utilized in a pilot study of image processing to determine any relationships between field collected and image data.

7-4-5-4. The Gradient Concept in the Image Processing for BSC Cover Detection

The procedure for characterizing a piosphere response in image-based remote sensing of BSC required GIS layers, such as a paddock boundary, a water source, a response indicator (i.e. BSC, bare soil, perennial, annual, litter, total photosynthetic components cover) and a raster response of index layer (i.e. TM derived index). The basic concept for piosphere analysis used a vector-based layer derived from ground-collected data versus a raster layer (index layer derived from TM imagery) which was conducted at different distances from water points. The response index layer was representative of a statistic or sum of the variable of surface attributes on a few pixels (i.e. vascular plants, BSC, bare ground and litter cover) in the sample locations. The response of vascular plants in dry and wet years have already been investigated and conceptualized in central Australia using this kind of model (Bastin *et al.*, 1993a; Pickup *et al.*, 1993; Pickup *et al.*, 1994; Pickup & Chewings, 1994). This study has initially taken BSC into account in graphical and numerical (i.e. correlation) analysis of pixel or index values using well developed indices such as the SSI, BSCI and NDVI (2-10). For index evaluation, polygon features derived from ground-collected data were correlated with derived raster index layers from TM imagery. Finally, the raster values of different band combinations of TM imagery were used for new index development. Each band combination was correlated with ground-collected data (i.e. BSC, bare ground, litter, etc) to examine the statistical significance. Band combinations with significant results, particularly for BSC cover, were also considered graphically.

7-4-5-5. Classification of Ground-collected Data for Index Calculation

The general procedures of data collection are described in Chapters 3, 4 and 6. This chapter generally used the same classification of land covers for index analysis (Appendices G-1, G-7 & G-8). As can be seen from these tables, nine land covers including bare ground, litter, perennials, annuals, BSC, vascular plants, total photosynthetic components and photosynthetic components with annuals (Appendix G-7) were utilized for the "Wet image" (2003/08/22) interpretation. For the "Dry season image" (2003/12/12) and "BSC image" (2004/06/05) bare ground, litter, perennial, BSC and total photosynthetic components without annuals (Appendix G-8) were the major land covers of

sampling locations for index calculation. This classification was used regarding the presence of each biotic element in the image acquisition time.

7-4-5-6. Classification or Pixel Value for Sample Locations

A pixel frame of TM imagery on the sample collected area by covering a line with 100 m in 30 sample locations at different distances of water points in five paddocks, was used for pixel value calculations. The polygon coverage values come from the collected ground-based data. The location of each sampling point was collected by the GPS. Although, there was a possibility of using buffering with 10 or 20 m distances for 100 m line-intercept transects, A "Zonal-based GIS Operation" or knowledge-based sample location selection on the field data collected area was performed. Zonal-based operations were performed on polygon layers for each sampling point in the ArcView v. 3.3. The rules of pixel inclusion were followed according to the ERDAS Imagine instruction for "Pixel Inclusion within Polygons", which can help to obtain the mean value of a group of pixels. Figure 7-5a & b shows the procedure of pixel selection for the polygons using the "Zonal Attributes Operation" for the calculation of pixel values of sample locations. There were two groups of polygon layers; a group of polygons where sampling transects were fitted to a group of pixels (Figure 7-5a) and a group of polygons when there was an angle problem to include the whole pixels around transects in the defined polygon (Figure 7-5b). In these cases, according to the rules of pixel inclusion, some of the pixels were selected by being half inside the polygon. For a mean polygon, those pixels that had their centre situated inside of the polygon, were used for index value calculation. The mean pixels value of each sample location was calculated usinig the procedure of the Zonal Attributes by ERDAS Imagine software for each image. Calculated pixel values were used as dependent components and the ground collected covers as independent components. This procedure was performed for raw and calibrated images in the index calculations.

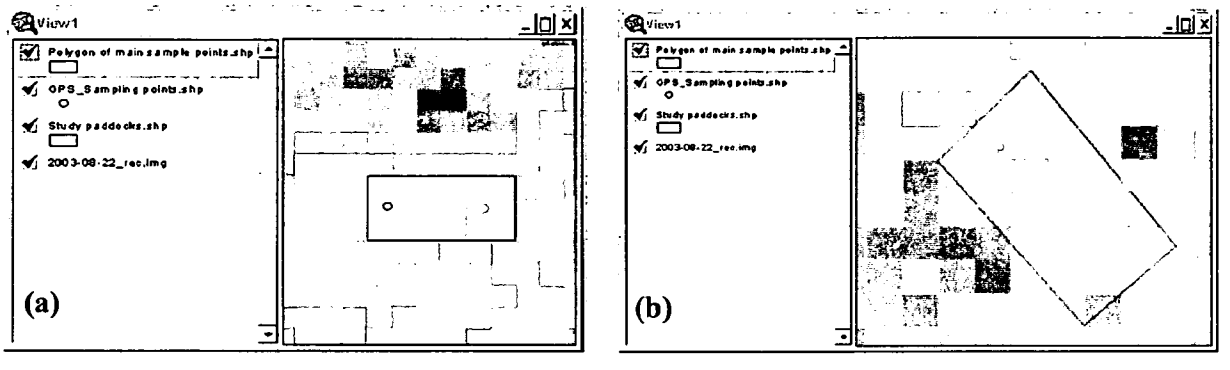

Figure 7-5. Polygon layer selection for pixel value calculation by "zonal-based attributes operation": a) A sample of polygon selection when sampling transects were fitted to groups of pixels and b) A sample of polygon when there was an angle problem to include the whole pixels around the transect.

7-4-5-7. TM Band Analysis

For testing developed indices and for developing new index analysis the correlation or carrying information by each band in the selected imagery was analyzed as:

TM Data Space

It seems that the approaches used for radiometric and atmospheric corrections, and for the conversion of data to exoatmospheric reflectances based on existing information, techniques and the dark pixel subtraction method of haze correction, does not remove all atmospheric effects. For checking the extreme values of different bands, particularly in the employed bands, mostly bands 1, 2, 3 and 4 were considered. This study has attempted to remove extreme values (if existing) from the data space before index calculations. This was achieved by exporting the ASCII format of digital number or reflectance values of each paddock using ERDAS Imagine. Exported data was plotted for different bands in Excel and in a few cases in the S-Plus spreadsheet (regarding the Excel limitation of large numbers of rows) for each paddock versus each other to examine the data patterns.

Principal Components Analysis

PCA is an important tool for analysis of image time series (Wang, 1993), and is often used as a method of data compression. It allows redundant data to be compacted into fewer bands, that is, the dimensionality of the data is reduced (Wang, 1993; Jensen, 1996). The bands of PCA data are non-correlated and independent, and are often more interpretable than the source data. PCA can be used to address such inter band correlation and separate that correlation into components (layers). The components that are generated consist of layers of information that are unique in their information content. Correlation between bands is viewed by most as redundancy (similar information in each band).

PCA has proven to be of value in the analysis of multispectral data. It has been conducted particularly to find a strong degree of correlation between the bands of a given multispectral dataset such as TM imagery (Wang, 1993; Jensen, 1996). It is not unusual to find that an image with 7 bands, such as TM imagery, actually contains far fewer than 7 bands of true information. For example, in most of the MSS data based derived indices according the high correlation between bands 6 and 7, band 6 is ignored (Pickup *et al.*, 1993). Since each of the components produced by this transformation is uncorrelated with the other, each carries new information. In this study, PCA was used to define first a few components and then the correlation of these components with the bands of TM images to define the importance of each band in carrying the captured information.

Scatterplots and Bands Correlation Analysis for the TM Data

To understand and define the relationships between different TM bands with each other for index testing and developing a new index, images of each paddock (using Area of interest tool) were tested using the Spatial Modeller Language of ERDAS Imagine to determine the relationships between different bands.

7-4-5-8. Index Calculation

There are three procedures of index calculation. Firstly, using image algebra to calculate the ratio of a portion of an image scene or the entire scene in order to represent the entire reflectance range of landscape features for a given index. Secondly, Cartesian plotting of each image band or band ratio on the x-axis versus band or band ratio on the y-axis such as the PD54 (2-10-3), and thirdly, using the equation of a given index to calculate index values (e.g. the NDVI). The procedure was the overlay of the ground collected points coverage against of the band ratio (index) images. This part of the study was conducted to develop indices for BSC detection. However, there was no opportunity to test the derived indices for other paddocks to validate the derived indices with a standalone remotely-sensed method.

7-4-5-9. Graphical Analysis of Piosphere

Derived pixel values for sampling locations were graphically considered to draw gradient patterns of the employed indices. For results interpretation, pre hypotheses were established as; the "Wet image" (2003/08/22) corresponds to the highest greenness and cover or soil stability value. The "BSC image" (2004/06/05) was hypothesized in the second level (cover and greenness or soil stability value). Finally, the "Dry season image" (2003/12/12) was hypothesized with the lowest greenness and cover or soil stability value. Thus, the derived pixel values of five paddocks were compared with the derived gradient patterns in Sections 4-5-2 and 4-5-3 from ground-based results. Moreover, they were compared with derived gradient models from NDVI values from ground-level spectra in Figure 6-7. The only limitation was for the "BSC image" (2004/06/05) where Corio paddock was under cloud, and thus in this image the other paddocks were used for comparison.

7-4-5-10. Development of a New BSC Index (Indices)

Indices have been intensively used for monitoring biophysical conditions and vegetation cover from satellite and airborne sensors (Pickup & Nelson, 1984; Bastin *et al.*, 1993a; Pickup *et al.*, 1993; Pickup *et al.*, 1994; Pickup & Chewings, 1994; Cameron & Lewis, 1996; Washington-Allen *et al.*, 2004; Chen *et al.*, 2005). Indices emphasize reflectance differences between materials and surface

information from two or more bands. The majority of the indices have been developed to detect bare soil, litter, rock and vascular plants. Very few studies such as CI and BSCI [In this thesis for "L" value in the BSCI (2-10-5), different amounts (1, 2, 3 ... 10) were tested, however the best results were taken by "L=2"] have focused on BSC detection.

By considering the ground-based gradient modelling of BSC cover (4-5-2 & 4-5-3), BSC spectral characterization (Ch.5), BSC gradient modelling by ground-level spectra (Figure 6-7) and TM capabilities (2-8), this part of the study was conducted to develop a new index according to the following steps:

a) As described earlier, understanding band correlation and carrying information of each band.

b) Understanding previous indices: testing some of the well developed and commonly used indices in the world, particularly in Australia to understand how they were developed and can work for BSC detection. Thus indices such as SR, NDVI, SSI, CI and BSCI have been tested using graphical and numerical analysis. It should be noted that the PD54 from the results of Chapter 5, does not work well for BSC detection, so it was not tested by image data. Expected results were classified as the representative of the greenness / cover value for the indices such as the SR, NDVI, CI and BSCI and stability value for the indices such as the SSI. These indices were chosen because they were computationally simpler and there is very little information about the effects of BSC cover on these commonly used indices, particularly in Australia.

   The indices used in this thesis have been mostly developed using MSS wavebands. The equivalent TM bands of 2 (green), 3 (red), 4 (NIR) corresponding to MSS bands 4 (green), 5 (red) and 6 (NIR) were used in this thesis.

c) For developing a new index, existing band ratios, field data, the cover value of the BSC, particularly from the soil stability and cover (greenness) value perspectives were considered in results interpretation. The main questions of this stage were: what are the results of the examination of the new index by numerical and graphical analysis and how to judge the robustness of the developed index.

d) For developing a new index, randomly different band combinations were considered initially and then the index value was tested with ground-collected cover data. If the correlation value was significant, the index was considered as a robust index from this stage, if the correlation value was not significant, other band combinations were tested for a new index.

7-4-5-11. Effects of BSC Cover in Remotely-sensed Data

To examine the effects of BSC cover in three images (By "Raw" and calibrated images), total cover of BSC was considered with bare ground and vascular plants collectively for indices analysis. The concept was if BSC cover in the data collection is assigned as bare soil or vascular plants, what would be the impact on image interpretation.

7-5. Results

For understanding the image and individual band characteristics the whole 60 × 60 Km of the TM scene, subset images of the area covered by five paddocks and finally individual paddocks were considered for band examinations. Some of the results are presented in the following sections.

7-5-1. Bands Correlation Analysis

Firstly, band correlation analyses for ground-level collected spectra in dry and wet conditions were conducted. Image data and PCA results for band correlations were considered secondly.

7-5-1-1. Ground-level Dry Spectra

As can be seen from Table 7-4, correlation between measured reflectances of four TM bands for 930 soil, stone, litter, shadow, vascular plants and BSC samples show that there is high correlation between band 1 and 2 ($r^2 = 0.8917$) and the lowest correlation exists between band 3 and 4 ($r^2 = 0.4898$).

Table 7-4. Correlation coefficient (r^2) between ground-level measured reflectances of the four synthesized TM bands of 930 soil, stone, shadow, vascular plant and BSC dry samples, and the digital value of four bands of TM image (Dry season image/2003/12/12) for Purpunda paddock

TM Bands	1	2	3	4
1	1.0000			
2	0.8917	1.0000		
3	0.6093	0.7683	1.0000	
4	0.5749	0.7202	0.4898	1.0000

7-5-1-2. Ground-level Wet Spectra

Table 7-5 shows the correlation between measured reflectances of four TM bands for 566 soil, stone, litter, shadow, vascular plants and BSC wet samples. High correlation exists between bands 1 and 2 ($r^2 = 0.9464$) and the lowest correlation exists between bands 3 and 4 ($r^2 = 0.4087$).

Table 7-5. Correlation coefficient (r^2) between ground-level measured reflectances of the four synthesized TM bands of 566 soil, stone, shadow, vascular plant and BSC wet samples, and the digital value of four bands of TM image (Dry season image/2003/12/12) for Purpunda paddock

TM Bands	1	2	3	4
1	1.0000			
2	0.9464	1.0000		
3	0.7375	0.7931	1.0000	
4	0.5817	0.7041	0.4087	1.0000

7-5-1-3. Correlation between Different Bands of TM Imagery

Table 7-6 shows the correlations between different bands and a scatter plot of the "Dry season image" (2003/12/12) for Purpunda paddock. From image data in Purpunda paddock, the lowest correlation exists between band 1 and band 7 ($r^2 = 0.5586$), and the highest correlation exists between band 5 and band 7 ($r^2 = 0.9457$). See band selection according to the correlation value by Graetz and Gentle (1982) and Pickup *et al.*(1993).

Table 7-6. Correlation coefficient (r^2) between different bands of the TM for calibrated "Dry season image" (2003/12/12) for Purpunda paddock

TM Bands	1	2	3	4	5	7
1	1.0000					
2	0.8527	1.0000				
3	0.6863	0.8802	1.0000			
4	0.6504	0.8505	0.9425	1.0000		
5	0.6465	0.8087	0.8712	0.8555	1.0000	
7	0.5586	0.7389	0.8614	0.8470	0.9457	1.0000

7-5-1-4. Correlation between Different Bands of TM Imagery and Ground Collected Data

As demonstrated in Table 7-7, bands 7 and 3 have the highest relationships ($p>0.05$) with different land covers in comparison with bands 1 and 2 with the lowest relationships. Bands 7 and 3 in the "Wet image" (2003/08/22) and "BSC image" (2004/06/05) have significant ($p>0.05$ & $p> 0.01$) relationships with bare soil. They have significant relationships ($p>0.05$) with BSC in the "BSC image" (2004/06/05). They have also significant relationships ($p>0.05$) with total photosynthetic elements (annual + perennial + BSC) in the "Wet image" (2003/08/22) when three elements (annual + perennial + BSC) are in the growing stage, and finally they have significant relationships ($p>0.05$ & $p> 0.01$) with total dry photosynthetic components (perennial + BSC) in the "BSC image" (2004/06/05). The other important result from the band analysis with collected land covers is the high relationships of BSC cover in different bands with the "Wet image" (2003/08/22) and "BSC image" (2004/06/05), when BSC were in the growth stage.

Table 7-7. Correlation coefficient (r^2) between TM bands / spectral response (COST image) and field measured percent covers for all land covers (n=30 for images 2003/08/22 and 2003/12/12) and (n=24 for image 2004/06/05). The column labelled vascular plants is the sum of annual and perennial. The column labelled total photosynthetic components is the sum of annuals, perennials and BSC cover. The column labelled bare soil + BSC is the representative of the situation, if BSC cover is assumed as bare soil in the image interpretation. The column labelled total dry photosynthetic components is the sum of perennial and BSC without annuals as the representative of the dry conditions when annuals are not in growing stage. Significant relationship are shown in bold / * $p > 0.05$, ** $p > 0.01$, *** $p = 0.001$

Band (Wavelength μm)	**Images**	**Bare ground**	**Litter**	**Annuals**	**Perennials**	**Vascular plants**	**BSC**	**Total photosynthetic components**	**Bare ground+ BSC**	**Total dry Photosynthetic components**
B1 / Blue (0.45-0.52)	2003/08/22	0.0437	0.0421	0.0134	0.1182	0.1090	0.0025	0.0253	0.1301	0.0097
	2003/12/12	0.0718	0.0575	-	0.2771	-	0.0069	-	0.0406	0.0211
	2004/06/05	0.0766	0.0286	-	0.0721	-	0.0281	-	0.0373	0.0719
B2 / Green (0.52-0.60)	2003/08/22	0.1938	0.0535	0.0010	0.0703	0.0330	0.0612	0.1556	0.0598	0.1230
	2003/12/12	0.1276	0.0918	-	0.2750	-	0.0003	-	0.0967	0.0585
	2004/06/05	0.1307	0.0010	-	0.0767	-	0.0654	-	0.0003	0.1243
B3 / Red (0.63-0.69)	2003/08/22	**0.4032***	0.0605	0.0254	0.0260	0.0006	0.2693	**0.3540***	0.0136	0.3275
	2003/12/12	0.3202	0.1297	-	0.2216	-	0.0766	-	0.3001	0.2210
	2004/06/05	**0.3683***	0.0144	-	0.0398	-	**0.3507***	-	0.0366	**0.3940***
B4 / Near Infrared (0.76-0.90)	2003/08/22	0.2071	0.0128	0.1030	0.1010	0.0142	0.2199	0.1983	0.0033	0.2477
	2003/12/12	0.2725	0.1028	-	0.1526	-	0.0891	-	0.2755	0.2061
	2004/06/05	0.1372	0.0657	-	0.0006	-	0.2222	-	0.1562	0.1771
B5 / Middle infrared (1.55-1.75)	2003/08/22	0.1467	0.0795	0.0005	0.0615	0.0402	0.0286	0.1019	0.0785	0.0730
	2003/12/12	0.1432	0.1371	-	0.2871	-	0.0003	-	0.1119	0.0612
	2004/06/05	0.2731	0.0018	-	0.1042	-	0.1815	-	0.0023	0.2789
B7 / Middle infrared (2.08-2.35)	2003/08/22	**0.3974***	0.0261	0.0214	0.0257	0.0010	0.2840	**0.3785***	0.0082	0.3426
	2003/12/12	0.2040	0.1016	-	0.2575	-	0.0167	-	0.1709	0.1174
	2004/06/05	**0.4696***	0.0066	-	0.0938	-	**0.3829***	-	0.0166	**0.4866****

On the other hand, in almost all bands, there are low relationships between the BSC cover and the "Dry season image" (2003/12/12) when BSC were in dry conditions. Finally, there is no significant relationship when BSC were assumed as bare ground (Bare soil + BSC = Bare soil).

7-5-1-5. Principal Component Analysis

Figure 7-6 presents the sreeplot of PCA for the "Dry season image" (2003/12/12) as an example for Purpunda paddock, in which 91% of information is carried by the first principal component (PC). The other five PCs are carrying less than 9% of information and are very low by the last PC. The results of PC correlation with TM bands are presented in Table 7-8. Results of this analysis show that; bands 5 and 7 of TM imagery are carrying the highest amount of information (r^2 = 0.9748 and r^2 = 0.9617) in comparison with other bands. Band 1 is carrying the lowest amount of information (r^2 = 0.6746). Because of the spectrometer wavelength limitations (350 to 1100 nm), 400 to 900 nm or 4 bands (1, 2, 3 and 4) of TM imagery were used in this thesis (Chs.5 and 6). However, bands 5 and 7 were also considered in index development, but without ground-level spectral analysis support.

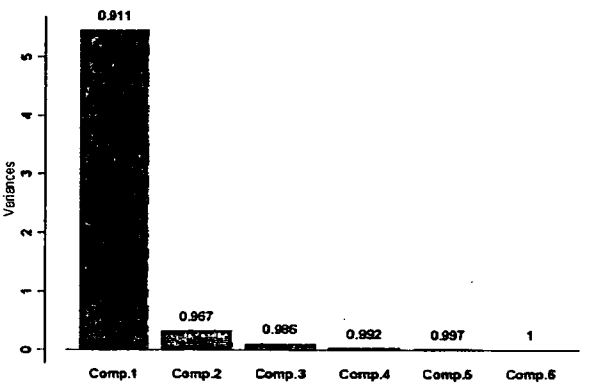

Figure 7-6. Screeplot of relative importance of principal components for Purpunda paddock of "Dry season image" (2003/12/12)

Table 7-8. Correlation coefficient (r^2) between different bands of the TM for calibrated "Dry season image" (2003/12/12) and different PCs for Purpunda paddock as an example

Bands \ Loading	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6
TMB 1	0.6746	0.4768	0.1558	0.2763	0.0172	0.0085
TMB 2	0.8587	0.5000	0.1424	0.1374	0.0002	0.1317
TMB 3	0.9441	0.4109	0.1366	0.0176	0.0245	0.0325
TMB 4	0.9351	0.4114	0.0327	0.0080	0.0030	0.0565
TMB 5	0.9748	0.1546	0.1410	0.1053	0.0101	0.0509
TMB 7	0.9617	0.1206	0.1915	0.0241	0.0004	0.0433

7-5-2. Statistical (Numerical) Analysis Results

Results of simple correlations between the field collected data and derived indices value for three images for "raw" and "calibrated" images are presented in Tables 7-9 and 7-10. Eight indices including the SR, Difference Vegetation Index (DVI), NDVI, Transformed Normalized Difference Vegetation Index (TNDVI), Infrared Percentage Vegetation Index (IPVI), SSI, CI and BSCI were examined for BSC detection and finally 5 indices including SR, NDVI, SSI, CI and BSCI were selected for presenting the results.

7-5-2-1. Raw Images

Table 7-9 shows the SSI has the best relationships ($p>0.01$) with the collected BSC cover. Some other indices such as the BSCI also have significant ($p>0.05$) relationships with BSC cover in the "BSC image" (2004/06/05). BSC cover has significant relationships ($p>0.05$) with the "Wet image" (2003/08/22) using SSI, BSCI and CI. Moreover, BSC cover, by employing the SSI and BSCI, has significant ($p>0.05$) relationships with the "Dry season image" (2003/12/12). BSC cover has no significant relationship with the SR and NDVI in any of the three images. However, the index values are higher for the BSC (2004/06/05) and Wet (2003/08/22) images versus low value for the "Dry season image" (2003/12/12). Only bare soil as the individual land cover, except BSC cover, has significant relationships with different indices in different images. The SSI for bare soil estimation had given the best results ($p>0.05$ & $p>0.01$). There are no significant relationships between individual land covers such as litter, annuals and perennials with the employed indices in three images. As Table 7-9 shows, all indices have low correlations with bare ground + BSC cover. On the other hand, if BSC were considered as a photosynthetic element, relationships for employed indices would be increased. The mixed total photosynthetic cover (BSC+ annuals+ perennials) had unexpected results of insignificant relationships for SR and NDVI with the "Wet image" (2003/08/22). However, other indices such as the SSI, CI and BSCI had significant ($p>0.05$ & $p>0.01$) relationships with total photosynthetic components. Overall, from the "Raw images", the SSI and BSCI can be used for an area in which BSC occur.

7-5-2-2. Calibrated Images

As can be seen from Table 7-10, the SSI and BSCI had the highest significant relationships ($p>0.05$ & $p>0.01$) with BSC cover. The CI also has significant ($p>0.01$) relationships with the "Wet image" (2003/08/22). BSC cover has no significant relationships with BSCI, SR and NDVI in any of the three images.

Table 7-9. Correlation coefficient (r^2) between image indices (Raw images) and field measured percent covers for all land covers (n=30 for images 2003/08/22 and 2003/12/12 and n=24 for image 2004/06/05). The column labelled vascular plants is the sum of annuals and perennials. The column labelled total photosynthetic components is the sum of annuals, perennials and BSC cover. The column labelled bare soil + BSC is representative of the situation, if BSC cover is assumed as bare soil in the image interpretation. The column labelled total dry photosynthetic components is the sum of perennial and BSC cover without annuals as the representative of the dry conditions when annuals are not in the growing stage. Significant relationships are shown in bold / * $p > 0.05$, ** $p > 0.01$, *** $p = 0.00$

Index	Images	Bare ground	Litter	Annuals	Perennials	Vascular plants	BSC	Total photosynthetic components wet condition	Bare ground + BSC	Total photosynthetic components dry condition
SR	2003/08/22	**0.4115***	0.1036	0.0007	0.0308	0.0220	0.1878	0.3356	0.0631	0.2448
	2003/12/12	0.1494	0.1070	-	0.2701	-	0.0086	-	0.2327	0.0979
	2004/06/05	0.2167	0.0262	-	0.0625	-	0.2093	-	0.0036	0.2767
NDVI	2003/08/22	**0.4211***	0.1133	0.0236	0.0316	0.0242	0.1879	0.2931	0.1084	0.1720
	2003/12/12	0.1494	0.1071	-	0.2649	-	0.0090	-	0.2301	0.0978
	2004/06/05	0.3221	0.0257	-	0.0616	-	0.2116	-	0.0032	0.2828
SSI	2003/08/22	**0.5042****	0.0587	0.0357	0.0047	0.0040	**0.4125***	**0.4558****	0.0272	**0.4252***
	2003/12/12	**0.5282****	0.0715	-	0.0398	-	**0.3736***	-	0.0032	**0.4597****
	2004/06/05	**0.4193***	0.0228	-	0.0143	-	**0.4633****	-	0.0930	**0.4550***
CI	2003/08/22	**0.4390***	0.0431	0.0614	0.0033	0.0114	**0.3999**	**0.4037***	0.0016	**0.4068***
	2003/12/12	0.3364	0.0698	-	0.0312	-	0.2176	-	0.0032	0.2788
	2004/06/05	0.3582	0.0209	-	0.0195	-	0.3803	-	0.0822	**0.3899***
BSCI	2003/08/22	**0.4792****	0.0484	0.0537	0.0022	0.0111	**0.4334***	**0.4395***	0.0001	**0.4307***
	2003/12/12	**0.4371***	0.0408	-	0.0073	-	**0.3713***	-	0.0029	**0.3936***
	2004/06/05	**0.4002***	0.0278	-	0.0118	-	**0.4530***	-	0.1023	**0.4395***

Table 7-10. Correlation coefficient (r^2) between indices of calibrated image (COST) and field measured percent covers for all land covers (n=30 for images 2003/08/22 and 2003/12/12 and n=24 for image 2004/06/05). The column labelled vascular plants is the sum of annuals and perennials. The column labelled total photosynthetic components is the sum of annuals, perennials and BSC cover. The column labelled bare soil + BSC is representative of the situation, if BSC cover is assumed as bare soil in the image interpretation. The column labelled total dry photosynthetic components is the sum of perennials and BSC cover without annuals as the representative of the dry conditions when annuals are not in the growing stage. Significant relationships are shown in bold / * $p > 0.05$, ** $p > 0.01$, *** $p = 0.001$

Index	Images	Bare ground	Litter	Annuals	Perennials	Vascular plants	BSC	Total photosynthetic components wet condition	Bare ground + BSC	Total photosynthetic components dry condition
SR	2003/08/22	**0.4228***	0.0930	0.0015	0.0303	0.0116	0.2202	**0.3523***	0.0441	0.2805
	2003/12/12	0.2205	0.1272	-	0.3130	-	0.0242	-	0.2425	0.1526
	2004/06/05	**0.3825***	0.0183	-	0.1465	-	0.2135	-	0.0220	0.3442
NDVI	2003/08/22	**0.4374***	0.0957	0.0005	0.0322	0.0149	0.2211	**0.3647***	0.0502	0.2838
	2003/12/12	0.2217	0.1278	-	0.3050	-	0.0256	-	0.2393	0.1535
	2004/06/05	**0.3915***	0.0150	-	0.1429	-	0.2256	-	0.0198	**0.3558***
SSI	2003/08/22	**0.5135****	0.0544	0.0391	0.0007	0.0100	**0.4522****	**0.4688****	0.0005	**0.4402***
	2003/12/12	**0.4007***	0.0339	-	0.0000	-	**0.3833***	-	0.0104	**0.3638***
	2004/06/05	**0.4327***	0.0176	-	0.0216	-	**0.4556***	-	0.0652	**0.4637****
CI	2003/08/22	0.3128	0.0069	0.1136	0.0197	0.0965	**0.4724****	0.3178	0.0539	**0.3675***
	2003/12/12	0.0829	0.0001	-	0.0665	-	0.1733	-	0.1068	0.0859
	2004/06/05	0.1791	0.0282	-	0.0011	-	0.2625	-	0.1655	0.2071
BSCI	2003/08/22	**0.3510***	0.0393	0.0593	0.0185	0.0020	0.2837	0.3185	0.0015	0.3302
	2003/12/12	0.3076	0.1073	-	0.2263	-	0.0844	-	0.1183	0.2358
	2004/06/05	0.2772	0.0300	-	0.0154	-	0.3051	-	0.0712	0.3123

However, the index values are high for the BSC (2004/06/05) and Wet (2003/08/22) images versus low for the "Dry season image" (2003/12/12). Only bare soil as the individual land cover, except BSC, has significant relationships with different indices ($p>0.05$ & $p>0.01$). The SSI for bare soil estimation had given the best results ($p>0.05$ & $p>0.01$). There are no significant relationships between individual land covers such as litter, annuals and perennials with the employed indices in three images. As Table 7-10 shows, all indices have very low correlations when BSC is assumed to be bare ground (BSC + Bare soil =Bare soil). On the other hand, if BSC cover was considered as photosynthetic components (BSC + Annuals + Perennials), relationships for employed indices have increased. Total photosynthetic cover (BSC + Annuals + Perennials) had unexpected results as insignificant relationships for SR, NDVI, and BSCI with the "Wet image" (2003/08/22). However, the SSI had significant ($p>0.05$ & $p>0.01$) relationships with total photosynthetic components. Overall, from the calibrated image results, the SSI can be concluded as the best existing index, which can be used for the area in which BSC are common. Unexpectedly the statistical results (as significant) for "Raw images" (27 significant correlations) in comparison with "calibrated images" (20 significant correlations) are reduced for all land covers. Thus from these results radiometric calibration of remotely-sensed data is a crucial step for rangeland monitoring, particularly for BSC detection.

7-5-3. Graphical Results for Gradient Identification

As pointed out earlier (Chs. 5 & 6), for gradient identification some indices such as the SSI, NDVI, CI and BSCI were selected to test the concept of gradient and effects of BSC. The results of employed indices in addition to the correlation coefficient were considered using graphical analysis. The graphical analyses were used for both calibrated (Figure 7-7) and Raw images (Figure 7-8). The graphical results of the calibrated images are considered in two groups: groups of indices for greenness or cover value estimation; and groups of indices for soil stability estimation. Different indices such as the SR, DVI, NDVI, TNDVI, SSI, CI and BSCI were tested graphically, and some of the best results are presented in this section.

7-5-3-1. Calibrated Images

NDVI

Figure 7-7a shows the graphical results of the calibrated images for five paddocks and six distances for the NDVI. The "Wet image" (2003/08/22)— which has the greenness value of annuals, perennials and BSC— has the highest index value; the "BSC image" (2004/06/05)—

which has only perennials and BSC cover greenness value— in the second level, and the "Dry season image" (2003/12/12)— which has only perennials greenness value— in the third level. For the "Wet image" and the "BSC image", there are distinguishable gradient patterns as a kind of "composite gradient" (2-7). The "Dry season image" also has a kind of "composite" (2-7) with small change in the patterns at the end of the gradients. Finally, regardless of the insignificant relationships of land covers with the NDVI in the correlation coefficient, although there are slight differences, particularly at 100 m from the water point, results of this index has supported the ground-based cover data by considering BSC cover at dry and wet conditions in the gradient patterns (4-5-2, 4-5-3 & Figure 6-7).

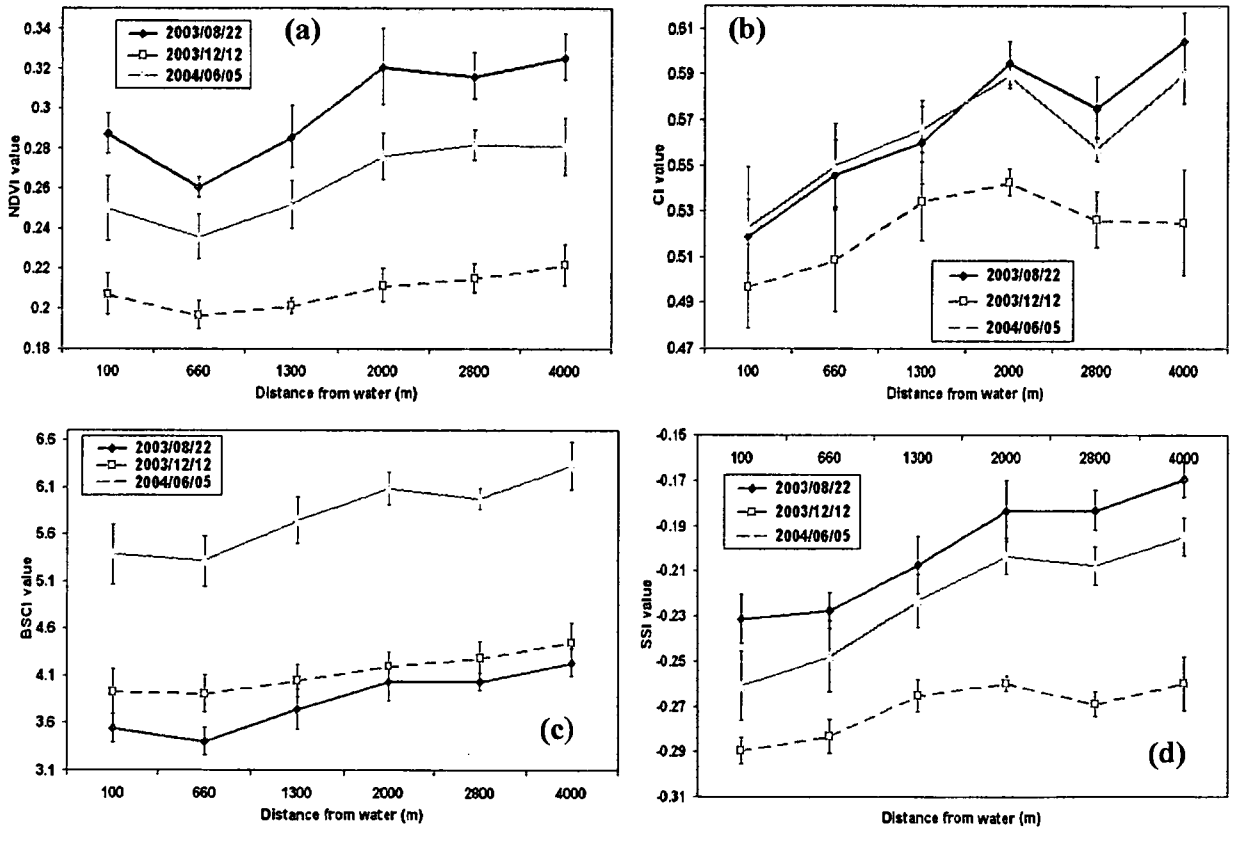

Figure 7-7. Graphical results of the tested indices with calibrated (COST) images: a) NDVI; b) CI; c) BSCI, and d) SSI

Spectral Crust Index

By considering the fact that band 1 is carrying the lowest amount of information and also CI was developed for cyanobacteria-dominated areas, results of the CI had some mixed patterns for the lichen-dominated rangelands at MFC. The results demonstrated that the "Wet image" (2003/08/22) and the "BSC image" (2004/06/05) in comparison with the "Dry season image" (2003/12/12) had considerably higher values (Figure 7-7b). However, the differences between the Wet and BSC

images were not conclusive. Overall, regardless of weak correlations of this index with the three images, derived results supported the ground collected and modelled grazing gradient pattern as being higher for the Wet and BSC images than for the "Dry season image", however with weak relationships for this index and graphical results for different images it is not an appropriate index for the study area.

Biological Soil Crust Index

A graphical result (Figure 7-7c) of the gradient of the BSCI for the "Dry season image" (2003/12/12) was unexpected in comparison with the Wet (2003/08/22) and BSC (2004/06/05) images. This was because, hypothetically the value or gradient pattern for the "Dry season image" was expected as the lowest (cover value) or highest (as lowest stability value) in comparison with the two other images. Overall, regardless of some significant relationships of this index with BSC cover, particularly in the "Raw image" (Table 7-9), the graphical results demonstrated that there is difficulty in the interpretation and use of this index for BSC detection at MFC.

Soil Stability Index

The SSI was developed to define soil stability status (2-10-2). As demonstrated in Figure 7-7d, the "Wet image" (2003/08/22) has the highest value, the "BSC image" (2004/06/05) in the second level and the "Dry season image" (2003/12/12) in the third level. By considering the concept of this index as measuring soil stability and the ecological role of BSC as an effective element, results show that it is a suitable index for BSC monitoring. Gradient patterns for all images are almost similar to the derived gradient patterns by ground collected data (4-5-2 & 4-5-3) and ground-level spectral modelling patterns in Figure 6-7. Overall, the SSI is the best existing index for BSC monitoring between the employed indices.

7-5-3-2. Raw Images

As demonstrated in Table 7-9, "Raw images" have higher correlations with BSC and bare soil in comparison with the calibrated images for some of the indices. The results of employed indices, as were expected in comparison with the pre-defined hypotheses, indicates the "Wet image" (2003/08/22) with the high cover value. "BSC image" in the second and "Dry season image" in the third level were not interpretable. Overall, results of numerical analyses of non calibrated images can easily cause misinterpretation for gradient identification using remotely-sensed methods. Derived graphs for different indices using "Raw images" are presented in Figure 7-8a-d.

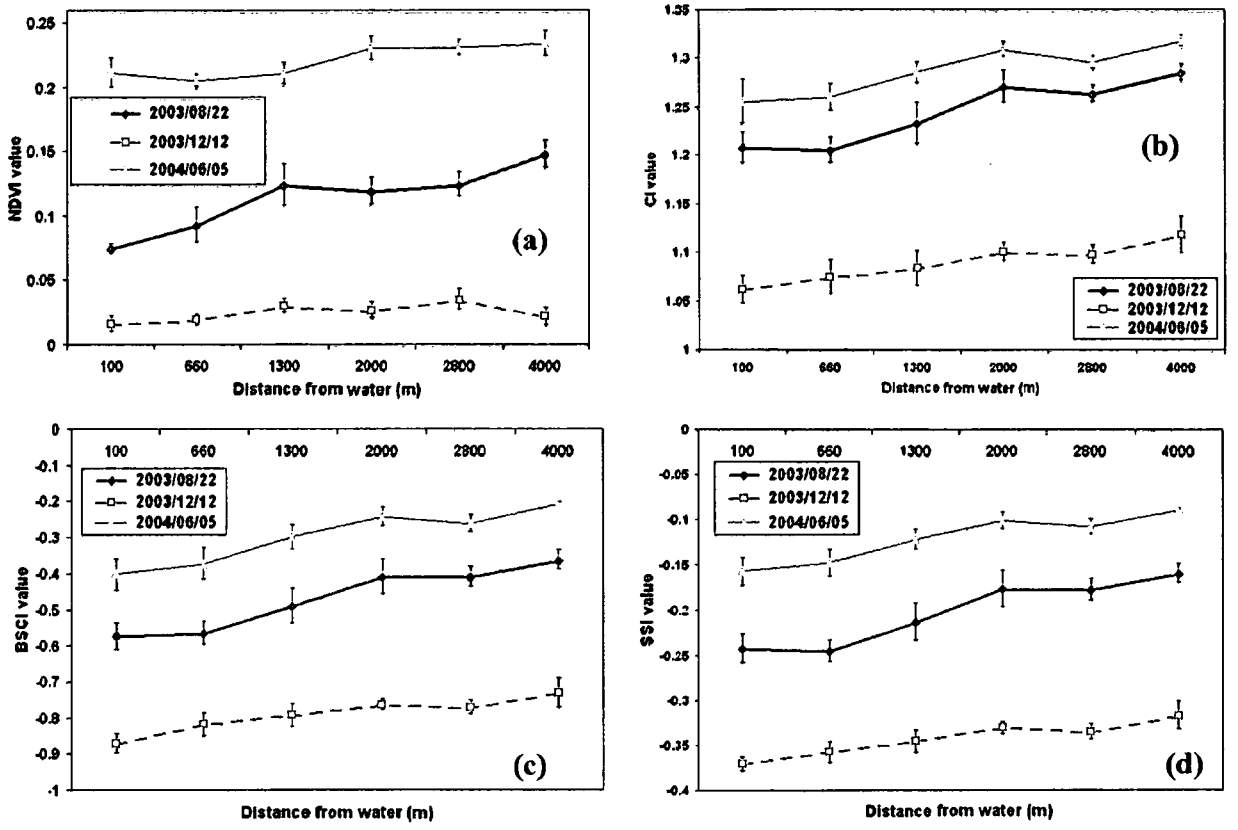

Figure 7-8. Graphical presentation of the employed indices in "Raw images": a) NDVI; b) CI; c) BSCI, and d) SSI

7-5-4. New Indices for BSC Detection

The results of the existing cover and soil stability indices show the possibility of detecting BSC in shrubland communities at MFC. These indices were developed with the aim of vascular plant or soil stability detection on areas where BSC was not common; therefore, this section was conducted in order to develop a possible index for detecting BSC using ground-collected data. The concept was using a fraction of different band combinations to pursue the possibility of developing a new index, better than the SSI, for BSC mapping. This study was mostly based on the bands 1 to 4 of TM imagery. However, the results of band analyses show the importance of bands 5 and 7 for BSC detection. Thus, in addition to the 4 mentioned bands, these bands were also considered in index development. By considering different random band combinations, finally eight new indices with the best results were selected for BSC detection (Table 7-11). The derived indices were tested in different paddocks with the collated data from the ground-based study with a dominance of BSC and shrubland as an index validation procedure to determine their significance for BSC monitoring. As mentioned in the method section, different possibilities of band combinations for new index development were randomly considered. Finally, the indices with significant

relationship with BSC cover, bare soil or photosynthetic components were kept as a robust index for BSC detection. It should be noted that to determine which one is the best index, a standalone remotely-sensed study is required with image selection, image interpretation using these indices and random sample selection for ground-truthing and accuracy assessment.

Table 7-11. New developed indices for BSC detection

BSC indices	Formulations
BSC_1	1 - (Red - Green) / (Red + Green) or 1-(B3-B2) / (B3+B2)
BSC_2	1 - (Red - Green) / (Red + Blue) or 1-(B3-B2) / (B3+B1)
BSC_3	2 - (Red / Near Infrared) / (Green / Near Infrared) or 2-(B3/B4) / (B2/B4)
BSC_4	1 - (Green * Near Infrared) / (Red * Near Infrared) or 1-(B2*B4) / (B3*B4)
BSC_5	(Red - Green) / ((Red + Green + Near Infrared) /3) or (B3-B2) / ((B3 +B4)/3)
BSC_6	(Green-Red) / (Green-Near Infrared) or (B2-B3) / (B2-B4)
BSC_7	(Green/Middle Infrared) – (Red/Middle Infrared) or (B2/B5)-(B3/B5)
BSC_8	(Green-Red) / (Green-Middle Infrared) or (B2-B3) / (B2-B5)

7-5-5. Statistical (Numerical) Analysis of New BSC Indices

7-5-5-1. Raw Images

Results of the developed indices for the "Raw images" are presented in Table 7-12. According to this table, BSC cover has significant relationships ($p > 0.05$) with the newly developed indices. New developed indices also have significant relationships ($p>0.05$ & $p > 0.01$) with total photosynthetic components (perennial + annual +BSC) in wet conditions, total photosynthetic components (perennial + BSC) in dry conditions and bare soil with the Wet (2003/08/22) and BSC (2004/06/05) images. On the other hand the "Dry season image" has the lowest correlation value and in some cases insignificant relationships with most of the land covers. More importantly, regarding the importance of band 5, the newly developed indices with a middle infrared band has no significant relationship with different land covers using "Raw images".

7-5-5-2. Calibrated Images

Results of the newly developed indices for calibrated images are presented in Table 7-13. According to this table, BSC cover has significant relationships ($p>0.05$, $p> 0.01$ & $p>0.001$) with BSC_1, BSC_3, BSC_4 BSC_5, BSC_6 and particularly with MIR-based indices including BSC_7 and BSC_8. Although, BSC_2 had significant relationships with the "Raw images", relationships of that with calibrated images were insignificant. Despite this insignificant relationship, the BSC_2 was maintained in order to validate a possible study with a standalone remotely-sensed method.

Table 7-12. Correlation coefficient (r^2) between image indices (Raw image) and field measured percent covers for all land covers (n=30 for images 2003/08/22 and 2003/12/12 and n=24 for image 2004/06/05). The column labelled vascular plants is the sum of annuals and perennials. The column labelled total photosynthetic components is the sum of annuals, perennials and BSC cover. The column labelled bare soil + BSC is the representative if BSC assumed as bare soil in the image interpretation. The column labelled total dry photosynthetic components is the sum of perennials and BSC covers without annuals as representative of the dry condition when annuals are not in the growing stage. Significant relationships are presented in bold for * $p > 0.05$, ** $p > 0.01$, *** $p = 0.001$.

Index	Images	Bare ground	Litter	Annuals	Perennials	Vascular plants	BSC	Total photosynthetic components wet condition	Bare ground + BSC	Total photosynthetic components dry condition
BSC_1	2003/08/22	**0.4581****	0.0207	0.0689	0.0006	0.0199	**0.4455***	**0.4254***	0.0018	**0.4323***
	2003/12/12	**0.3686***	0.0246	-	0.0005	-	**0.3580***	-	0.0157	0.3406
	2004/06/05	**0.3844***	0.0316	-	0.0090	-	**0.4466***	-	0.1122	**0.4261***
BSC_2	2003/08/22	0.4691	0.0638	0.0314	0.0010	0.0244	**0.3939***	**0.4167***	0.0007	**0.3873***
	2003/12/12	0.2976	0.1922	-	0.0004	-	**0.2046**	-	0.0127	0.2002
	2004/06/05	**0.3827***	0.0331	-	0.0113	-	**0.4390***	-	0.1175	**0.4253***
BSC_3	2003/08/22	0.4661	0.0240	0.0636	0.0007	0.0177	**0.4450***	**0.4317***	0.0011	0.4331
	2003/12/12	0.3768	0.0266	-	0.0005	-	**0.3647***	-	0.0153	0.3468
	2004/06/05	**0.3874***	0.0329	-	0.0099	-	**0.4484***	-	0.1122	**0.4223***
BSC_4	2003/08/22	0.4512	0.0393	0.0726	0.0005	0.0216	**0.4449***	**0.4195***	0.0023	**0.4303***
	2003/12/12	**0.3629***	0.0233	-	0.0003	-	**0.3731***	-	0.0159	0.3362
	2004/06/05	**0.3816***	0.3070	-	0.0083	-	**0.4448***	-	0.1123	**0.4223***
BSC_5	2003/08/22	0.4889	0.0484	0.0535	0.0019	0.0115	**0.4337***	**0.4413***	0.0005	**0.4332***
	2003/12/12	0.4330	0.0392	-	0.0060	-	**0.3731***	-	0.0038	**0.3910***
	2004/06/05	**0.4012***	0.0277	-	0.0113	-	**0.4556***	-	0.1036	**0.4404***
BSC_6	2003/08/22	**0.5022****	0.0822	0.0047	0.0172	0.0033	0.3084	**0.4315***	0.0272	**0.3536***
	2003/12/12	0.2239	0.1259	-	0.2404	-	0.0363	-	0.2003	0.1558
	2004/06/05	**0.4531***	0.0083	-	0.0219	-	**0.4647***	-	0.0619	**0.4728***
BSC_7	2003/08/22	0.3279	0.0107	0.0377	0.001	0.0088	0.3221	**0.3268**	0.0016	0.3118
	2003/12/12	0.2616	0.0011	-	0.0006	-	0.2731	-	0.0374	0.2674
	2004/06/05	0.2540	0.0547	-	0.0049	-	0.3210	-	0.0775	0.3013
BSC_8	2003/08/22	0.2638	0.0022	0.0279	0.0013	0.0054	0.2645	**0.2760**	0.0019	0.2645
	2003/12/12	0.1666	0.0001	-	0.0004	-	0.1812	-	0.0041	0.1777
	2004/06/05	0.1721	0.0699	-	0.0055	-	0.2254	-	0.0435	0.2177

As described in Section 7-4-5, a pre-hypothesis for BSC detection was that the BSC (2004/06/05) and Wet (2003/08/22) images could be the best representatives of the BSC compared with the "Dry season image" (2003/12/12). Overall, newly developed indices, which were based on MIR bands, not only had the highest significance in relationship with BSC, bare soil and photosynthetic components, but results of those for the "Dry season image" were interesting, with the highest relationships value ($r^2 = 0.6013$ & p>001) between all indices in calibrated images. It should be noted that previous studies generally presumed that most spectral information about biological elements can be derived from the visible and NIR regions. Only few studies focused on MIR and SWIR regions. The significant results for MIR may be attributed to the architecture of the biological elements including BSC at MFC. For example, BSC cover in most of the cases at MFC is the second land cover and probably different from the study sites of other studies. Newly developed indices, except BSC_2 have significant relationships ($p > 0.05$), with total photosynthetic components in wet conditions and total photosynthetic components in dry conditions. Newly developed indices except BSC_2 also have significant relationships with bare soil in the "Wet image" (2003/08/22), but, there are no significant relationships with other images. Overall results for "Raw images" was 50 significant correlations for different land covers, however in comparison calibrated images had 48 significant correlations for the same land covers.

7-5-7. Graphical Analysis of New Indices

7-5-7-1. Calibrated Images

BSC_1, BSC_2 and BSC_3

BSC_1 is based on the band 2 (green) and band 3 (red) of the TM imagery. BSC_2 is based on the band 1 (blue), band 2 (green) and band 3 (red). BSC_3 is based on the band 2 (green), band 3 (red) and band 4 (NIR) of the TM imagery. Figures 7-9a, b and c show the amount of differences between the Wet and BSC images are low for these indices, however the pre-defined hypothesis is supported by the results as the "Wet image" (2003/08/22) has the highest value, the "BSC image" (2004/06/05) is in the second level and the "Dry season image" (2003/12/12) has the lowest value. The derived gradients pattern is almost supported by the derived gradients from ground collected data (4-5-2 & 4-5-3) and ground-level spectra modelling (Figure 6-7).

Table 7-13. Correlation coefficient (r^2) between indices of radiometric and atmospherically corrected image (COST) and field measured percent covers for all land covers (n=30 for images 2003/08/22 and 2003/12/12 and n=24 for image 2004/06/05). The column labelled vascular plants is the sum of annuals and perennials. The column labelled total photosynthetic components is the sum of annuals, perennials and BSC cover. The column labelled bare soil + BSC is the representative if BSC assumed as bare soil the image interpretation. The column labelled total dry photosynthetic components is the sum of perennials and BSC without annuals as representative of the dry conditions when annuals are not in the growing stage. Significant relationships are shown in bold for * $p > 0.05$, ** $p > 0.01$, *** $p = 0.001$.

Index	Images	Bare ground	Litter	Annuals	Perennials	Vascular plants	BSC	Total photosynthetic components wet condition	Bare ground + BSC	Total photosynthetic components dry condition
BSC_1	2003/08/22	**0.3636***	0.0165	0.0989	0.0105	0.0721	**0.4787****	**0.3555***	0.0320	**0.3928***
	2003/12/12	0.1241	0.0002	-	0.0778	-	0.2508	-	0.1253	0.1339
	2004/06/05	0.2773	0.0478	-	0.0005	-	**0.3985***	-	0.1732	0.3229
BSC_2	2003/08/22	0.2408	0.0291	0.0395	0.0011	0.0212	0.2527	0.2167	0.0033	0.2239
	2003/12/12	0.1140	0.0013	-	0.0541	-	0.2212	-	0.0741	0.1270
	2004/06/05	0.2312	0.0499	-	0.0012	-	0.3457	-	0.1178	0.2743
BSC_3	2003/08/22	**0.3700***	0.0169	0.0961	0.0100	0.0697	**0.4812****	**0.3616***	0.0304	**0.3964***
	2003/12/12	0.1321	0.0003	-	0.0781	-	0.2637	-	0.1312	0.1429
	2004/06/05	0.2828	0.0468	-	0.0002	-	**0.3993***	-	0.1714	0.3283
BSC_4	2003/08/22	**0.3591***	0.0164	0.1000	0.0110	0.0736	**0.4761****	**0.3509***	0.0329	**0.3894***
	2003/12/12	0.1195	0.0002	-	0.0775	-	0.2434	-	0.1219	0.1289
	2004/06/05	0.2734	0.0482	-	0.0009	-	**0.3973***	-	0.1742	0.3189
BSC_5	2003/08/22	**0.4663****	0.0376	0.0635	0.0007	0.0299	**0.4814****	**0.4367***	0.0052	**0.4374***
	2003/12/12	0.2346	0.0050	-	0.02630	-	0.3206	-	0.0647	0.2299
	2004/06/05	0.3688	0.0309	-	0.0050	-	**0.4428***	-	0.1127	**0.4091***
BSC_6	2003/08/22	**0.5292****	0.0739	0.0168	0.0075	0.0002	**0.3866***	**0.4687****	0.0089	**0.4095***
	2003/12/12	**0.5568*****	0.1369	-	0.1366	-	0.2801	-	0.0683	**0.4509****
	2004/06/05	**0.4838****	0.0021	-	0.0590	-	**0.4245***	-	0.0137	**0.4908****
BSC_7	2003/08/22	**0.4589****	0.0180	0.1187	0.0025	0.0608	**0.5591*****	**0.4528****	0.0250	**0.4952****
	2003/12/12	**0.4474***	0.0930	-	0.0174	-	**0.5505*****	-	0.0760	**0.4392***
	2004/06/05	0.3209	0.0462	-	0.0001	-	**0.4436***	-	0.1534	**0.3686***
BSC_8	2003/08/22	**0.4452***	0.0157	0.1191	0.0007	0.0505	**0.5333****	**0.4419***	0.0215	**0.4836****
	2003/12/12	**0.5833*****	0.0219	-	0.0001	-	**0.6013*****	-	0.0333	**0.5578*****
	2004/06/05	0.3202	0.042	-	0.0001	-	**0.4365***	-	0.1363	**0.3653***

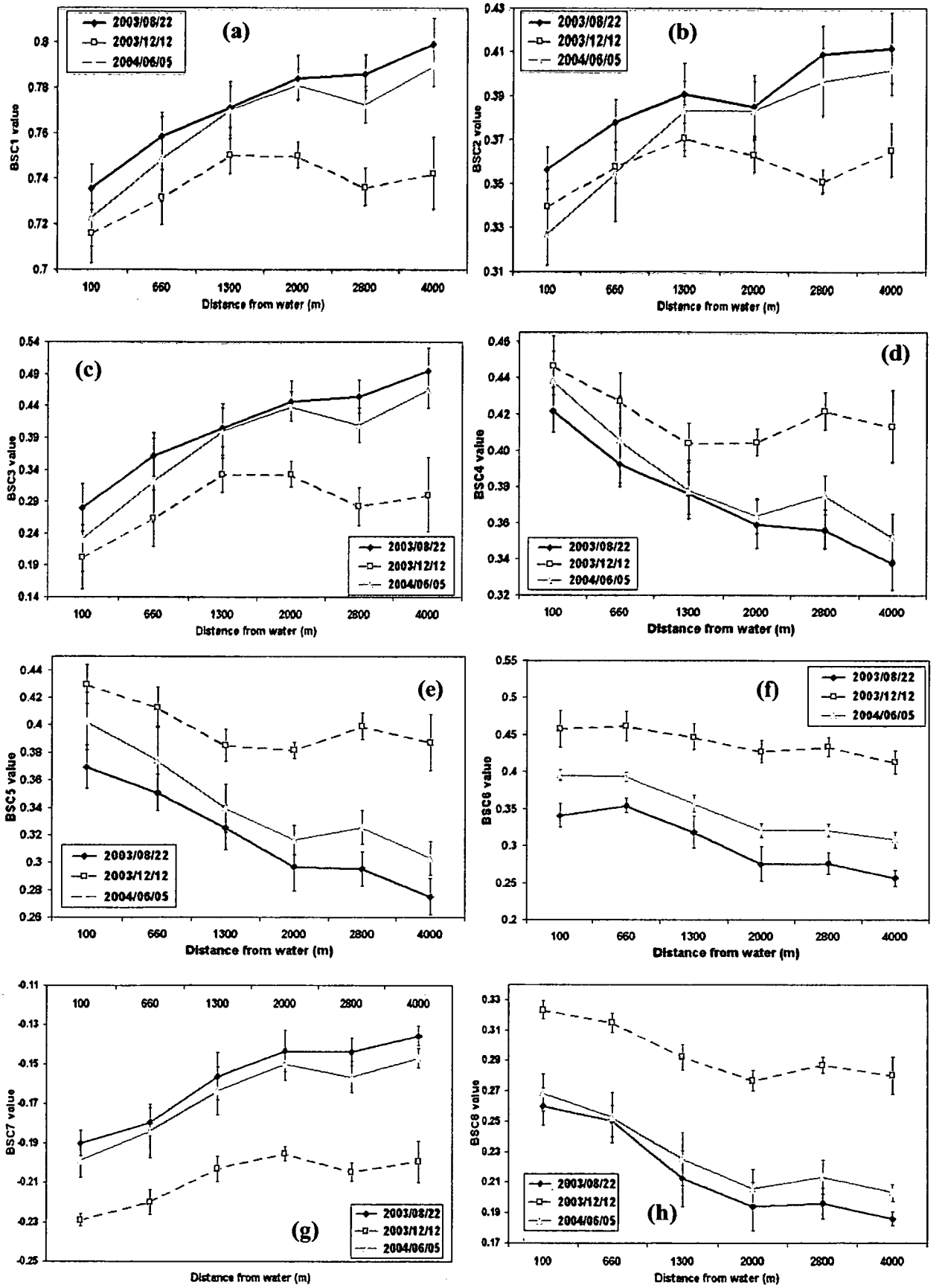

Figure 7-9. Graphical results of the new developed indices for calibrated (COST) images: a) BSC_1; b) BSC_2; c) BSC_3; d) BSC_4; e) BSC_5; f) BSC_6; g) BSC_7, and h) BSC_8

BSC_4, BSC_5, BSC_6 and BSC_8

BSC_4 and BSC_5 are based on band 2 (green), band 3 (red) and band 4 (NIR), however BSC_8 is based on band 2 (green), band 3 (red) and band 5 (MIR) of the TM imagery. The BSC_6 is actually based on the developed index by Foran and Pickup (1984). The only change is; instead of band 7 of MSS, band 4 of TM was used. Therefore, this index is based on band 2 (green), band 3 (red) and band 4 (NIR) the same as the BSC_4 and BSC_5. As Figures 7-9d, e, f and h show the results are contrary to expectations, as the "Wet image" (2003/08/22) has the lowest value, the "BSC image" (2004/06/05) is in the second level and the "Dry season image" (2003/12/12) has the highest value. By considering the SSI, field collected data and correlation results, it can be interpreted as the soil stability index rather than the cover index in shrubland communities at MFC. The concept for interpretation of those could be assumed as the lowest value as the highest stability value and the highest value as the degraded area with the lowest stability value. Conceptualizing them for the application needs more investigation. However, the gradient pattern is opposed to the derived gradient patterns from ground collected data (4-5-2 & 4-5-3) and ground-level spectra modelling (Figure 6-7).

BSC_7

Most of the indices in the world, including Australia, were based on the visible and NIR bands. In the literature of Australia, the only employing of MIR bands for index development was conducted by Foran and Pickup (1984). From the results of band analysis, band 5 and 7 are carrying the most captured information by TM imagery. BSC_7 is the index, which is based on band 2 (green), band 3 (red) and band 5 (MIR) of TM imagery. Figure 7-9g shows the graphical results of this index for calibrated images. It is a type of cover index, with the highest value at different distance for the "Wet image" (2003/08/22), the "BSC image" (2004/06/05) at the second level and finally the "Dry season image" (2003/12/12) with the lowest value at the third level. Results of this index are similar to the developed gradient models by ground collected and ground-level spectral models for gradient patterns at MFC in Sections 4-5-2, 4-5-3 and Figure 6-7. It should be noted that in spite of the importance of band 7 of TM imagery, this study could not develop any considerable index based on this band.

7-5-7-2. Raw Images

As demonstrated in Table 7-12, previously developed indices calculated from "Raw images" have higher correlations with BSC and bare soil in comparison with calibrated images. In contrast, correlation values are low for MIR based- indices. Thus, it is better to use the "Raw images" if there is no need to undertake temporal image comparison. However, consideration of

the derived graphical results, despite significant correlation, reveals that there are mixed gradient patterns in comparison with the collected ground data and ground-level spectral modelling. The results of employed indices, as was expected in comparison with the pre-defined hypothesis, were not interpretable. Derived graphs for different indices are presented in Figure 7-10a-h.

7-5-8. Effects of BSC on TM Data

Tables 7-12 and 7-13 present that for both series of "Raw" and calibrated images BSC exert an influence on TM imagery. This is concluded from correlation coefficient values significance level for the mixed patterns of the BSC (BSC + bare soil=bare soil) and total photosynthetic components (BSC + vascular plants = total photosynthetic components). As can be seen from these tables, bare soil individually has significant relationships with existing and newly developed indices ($p>0.05$, $p>0.01$ & $p>0.001$), and BSC also has significant relationships ($p>0.05$ & $p>0.01$) with these indices. In contrast, annuals and perennials individually have no significant relationships, BSC cover, when merged with bare soil, shows a reduction in the significance of the relationships. On the other hand, when BSC is merged with other photosynthetic components in the wet and dry conditions the significance of the relationships was increased. Thus from these results there is an effect by BSC cover on remotely-sensed data, and results of image processing by considering BSC as bare soil or photosynthetic components could be completely different.

7-6. Discussion

7-6-1. Effects of Local to Regional Rainfall on BSC Growth and on Remotely-sensed Data

In the last three decades, the issues of global warming, loss of land productivity potential and degradation is of significant consideration for expressing the greenness value change when using remotely-sensed data, particularly course and medium scale satellites such as the Advanced Very High Resolution Radiometer (AVHRR), MODIS, Landsat and SPOT (Cridland *et al.*, 1995; Cridland & Fitzgerald, 2001; Lovell & Graetz, 2001; Allan *et al.*, 2003). These data are usually utilized in large areas such as the Gawler Range bioregion, central Australia, Australia's states and even the Australasian continent. As reviewed in Section 2-5, BSC is widespread in many parts of Australia. Rainfall distribution in arid and semi-arid environments has different patterns from local to regional level. For example, rainfall analysis at the 4 stations for this study showed that very high variations exist between the numbers of rainy days in Whyalla in comparison with the other stations. Thus, there is the high possibility of the effects of rainfall on the growth of BSC on one part of an image such as Landsat, but no effect in other parts of that image.

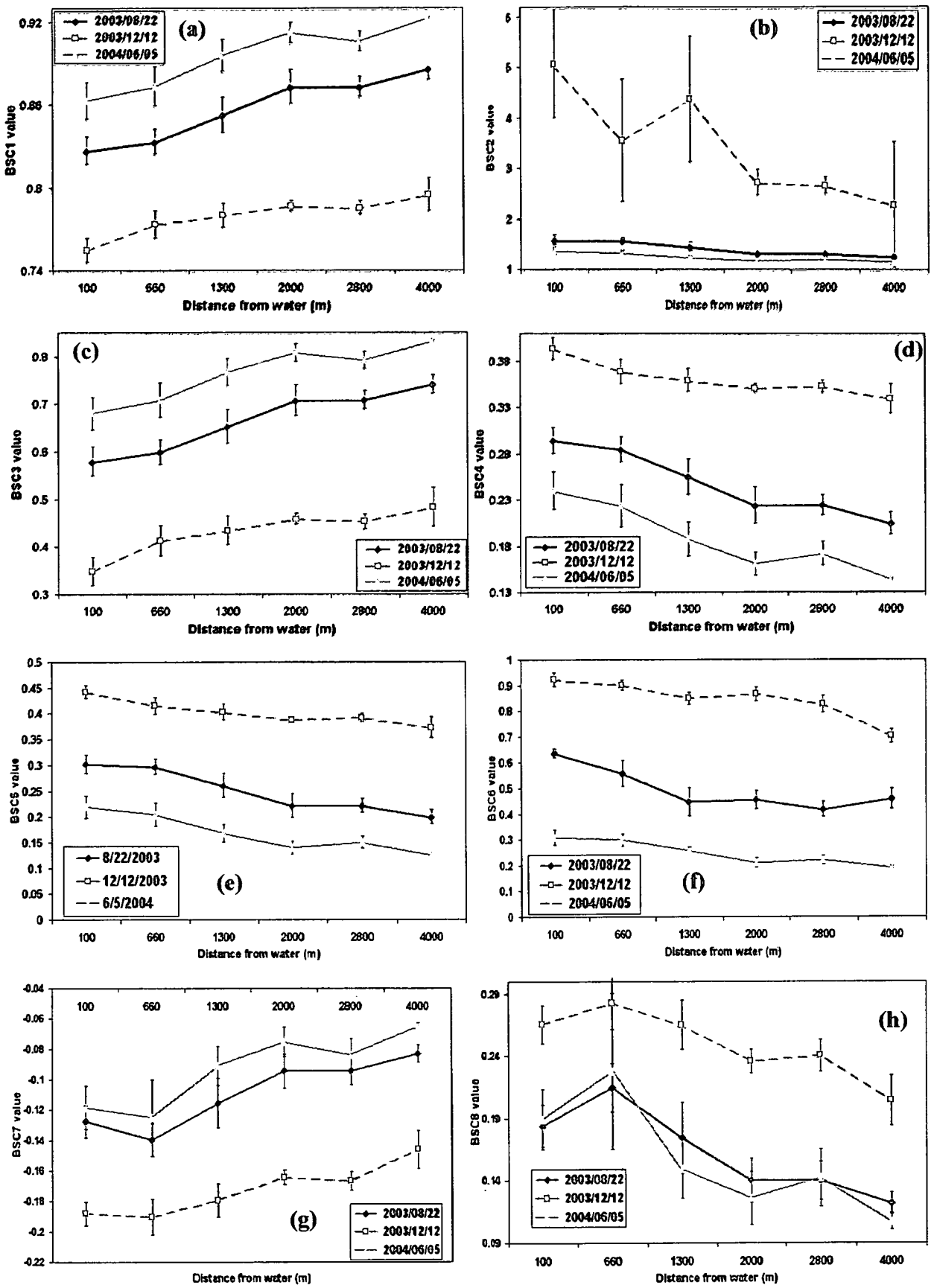

Figure 7-10. Graphical results of the new developed indices for "Raw images": a) BSC_1; b) BSC_2; c) BSC_3; d) BSC_4; e) BSC_5; f) BSC_6; g) BSC_7, and h) BSC_8

Thus, misinterpretation of the image by covering dry and wet BSC on the same image could be an important consideration. This possibility will increase using the small-scale satellite data such as the AVHRR and MODIS using the indices such as the NDVI. This study examined the spectral similarity among the different land covers for NDVI in dry and wet conditions (Ch. 6), and results showed that there are considerable differences between these conditions. Moreover, there is the possibility of the effects of rainfall on the BSC growth locally, which can create a heterogeneous growth on the same image, and in turn can create difficulty in applying other indices such as the plant health (Hatfield & Pinter, 1993), biomass and Leaf Area Index (Turner *et al.*, 1999; Gupta *et al.*, 2000), chlorophyll content (Haboudane *et al.*, 2002) and plant stress (Carter & Miller, 1994), if they are applied on the areas in which BSC occur with dry and wet heterogeneous conditions. Thus, for the application of these kinds of indices, particularly in the regional level, the rainfall pattern at image acquisition time should be considered from different stations rather than only one. The consequence for the area where rainfall data is either not available or very sparse is of concern and creates possible misinterpretation. Thus, rainfall and image selection on the area in which BSC occur is an important pre-consideration and should be checked from existing stations to define BSC growth patterns in an image covered area as dry or wet to reduce these effects. One of the possible solutions could be a method such as the Thiessen polygon (Appendix E-3) —rainfall affected area by each station— can be considered as the base of image interpretation.

7-6-2. Temporal Image Selection for BSC Detection

Results of spectral analysis and image data show that direct identification of BSC cover using remotely-sensed data is almost impossible. However, classification based on temporal image selection based on the phenological stages of BSC, annuals and perennials is possible. For this purpose some criteria such as prior knowledge of climatic and phenological patterns investigations (3-2-1, Appendix E & 7-4-2), spectral characterization (Ch.5) and ground-level spectral modelling (Ch.6) are required to examine this possibility accurately. This study derived information from climatic and phenological analysis, and developed an image selection process based on the study years' data. Temporal image selection in this thesis are more complicated, because of the three images selection instead of two in change detection studies (Bastin *et al.*, 1993a; Pickup *et al.*, 1994; Pickup & Chewings, 1994). Moreover, because of the close image selection time to the rainfall events, moisture is an important consideration in this approach. However, in some stages of this procedure there is uncertainty about the climatic and phenological patterns according to the short-term phenological observations for different

elements and this requires further investigation in each step to determine the real extent of each stage and standardize the image selection for BSC detection.

7-6-3. Radiometric Correction and Image Calibration Importance for BSC Detection

Radiometric correction is a critical stage in remote sensing analysis (Lillesand & Kiefer, 2000; Campbell, 2002). Results of this study showed that "Raw images" have higher correlations with BSC and bare soil in comparison with the calibrated images for some of the indices. Therefore, from these results it can be concluded that it is difficult to remove all atmospheric effects on the rangeland ecosystems, particularly when the aim is to select more than two temporally-based images. Image selection in this thesis was a function of growing seasons which is synchronized with low sun angle and high shadow effects (Graetz, 1987; Graetz *et al.*, 1988). This study has selected two images in winter-spring with high shadow effects in contrast to one summer image (7-4-3). There are high similarities of BSC spectra with shadow data (Ch.5), thus, as stated, by examining four methods of radiometric correction, a sun standardized method is recognized as an important radiometric correction method for BSC detection.

7-6-4. TM Band Analysis for Index Selection and Index Development

Band analysis of TM imagery showed that bands 1 and 2 have a high correlation to each other, however in comparison band 2 is carrying more information. Bands 5 and 7 have the highest correlation to each other, and band 5 is carrying more information. Thus, as concluded by previous studies such as Graetz and Gentle (1982) and Pickup *et al.*(1993), when there is high correlation between 2 bands, only one of them is necessary for index development. Although in index development all possible options using different bands of TM imagery were considered— from the results of band analysis— bands 2, 3, 4 and 5 of TM imagery were deduced as the important bands for index development for BSC detection. Considering literature such as Pickup *et al.* (1993) the visible green (band 2) and red (band 3) are more robust than the red-infrared indices for arid rangelands in Australia. The results of this study also support their claim, and these bands are considered in data analysis in Chapter 5. However, these bands in the Cartesian data space from the ground-level spectra, did not show promising results for BSC detection when utilizing the soil and vegetation lines (Ch.5). Visible / NIR band characteristics were investigated extensively by this study but MIR and SWIR bands, particularly from the ground-level spectral analysis perspective, require more investigation.

7-6-5. Image-derived Grazing Gradient Patterns in Comparison with Ground Data (Ground-based and Ground-level Spectral Modelling)

As discussed in Chapter 5, the role of BSC on the previously developed indices such as the PD54 is not clear. BSC at the image selection time of previous studies were dry (Cameron & Lewis, 1996; Lewis *et al.*, 2000; Lewis, 2000; Lewis *et al.*, 2001). Results of spectral analyses for six BSC groups individually showed that there are mixed patterns with high variations between the different spectra in dry and wet conditions. The individual spectra for BSC groups are mostly overlapped with litter, shadow and vascular plants (Ch.5), however "pattern spectra" are more similar to bare soil. Results of Sections 4-5-2, 4-5-3 and Figure 6-7 showed that derived grazing gradient patterns with and without BSC have considerably different cover values. Image derived grazing gradient patterns also showed that existing and newly derived indices with significant and insignificant relationships have strong associations with grazing gradient patterns with BSC cover considerations.

7-6-6. Capability of Existing Indices for BSC Detection

From the ground-level spectral modelling (Ch. 6), there was a strong association between BSC cover and derived grazing gradient patterns. However, image derived gradient patterns for the NDVI, although graphically showing strong association by BSC consideration, statistically results were not significant. Therefore, from these results the claims of previous studies were confirmed, that difficulty exists in transferring ground-level derived models to image analysis in a linear fashion (2-10-1). A second problem relates to the NDVI which is not the product of the process with which it is correlated (Rundquist, 2000). A third issue is the index value in dry versus wet conditions from the results of Chapter 6 in that NDVI values were increased for bare soil from dry to wet conditions. Thus there are the effects of wet bare soil on the derived indices which cannot be neglected in the image interpretation and may create problems for image analysis and more investigation is required. The results of the Simple Ratio index were almost similar to the NDVI.

As discussed in Chapters 5 and 6 the SSI showed some promising results for BSC detection by ground collected spectra. Results of this chapter also support the ground-level spectral analysis with significant relationships for "Raw" and calibrated images with the ground collected BSC cover. In comparison with the existing indices the results of this index had higher significant values. From the results of this chapter, the calculated amounts of the SSI for the three calibrated images varied from - 0.16 to -0.30 and for "Raw images" varied from -0.11 to -0.37, which is different from the results of Pickup and Nelson (1984) (2-10-2). If -0.23 is assumed to be a stable condition, -0.16 in calibrated images or -0.11 in "Raw images" can be

assumed as severe erosion and -0.30 in calibrated images or -0.37 in "Raw images" can be assumed as extensive deposition (Figure 2-5). Then, from these amounts for calibrated images, the "Dry season image" (2003/12/12) for all of the sites showed severe erosion conditions. In the "Wet image" (2003/08/22) 24 out of 30 sites showed stable to extensive deposition, and 6 sites with mild to stable conditions. Finally in the "BSC image" 17 out of 24 sites showed mild to stable and 7 sites with stable to extensive deposition conditions (Figure 2-5). From these interpretations, it can be concluded that there are effects of BSC and vascular plant growth stage signals on the SSI and a possible misinterpretation if images are selected on the dry state of BSC. Gradient patterns of this index supported the concepts (Figure 2-5) and derived patterns by ground collected data and spectrally derived patterns.

From the results of this study for CI, band 1 (blue) has the lowest correlation with the first Principal Component, which is carrying the most information. Moreover, this index was developed on the rangelands with the dominance of cyanobacteria, whereas MFC is a lichen-dominated rangeland (3-10). Therefore, in the case of this index, there is high probability of obtaining uncorrelated results, unless other combinations of the different bands are used in the index development. Results of this index for BSC detection showed insignificant relationships with BSC cover and support the pre-defined concept in which MFC is a lichen-dominated rangeland. Derived gradient patterns from image analysis although had similarity to the derived gradient patterns from ground collected cover data and spectrally derived gradient patterns, however conceptually there was mixed patterns (i.e. lower cover values for wet image and mixed cover values between BSC and Wet images) for dry and wet conditions.

BSCI has two limitations to apply for BSC monitoring at MFC; first this index was developed on an area with algae distribution and secondly Chen *et al.* (2005) concluded that the BSCI could be sensitive if BSC cover is more than 33%, however at MFC 22 out of 30 sites had less than 33%. Statistically although this index showed a significant relationship with "Raw images" however relationships for calibrated images were not significant and graphically there were mixed patterns, in contrast with the defined hypothesis (7-4-5) prior to image interpretation, as "Wet image" with the highest cover or stability value versus "Dry season image" with the lowest value.

Overall, the SSI is the best among the tested indices for BSC detection and BSCI, statistically and NDVI graphically are in the second stage. The other consideration from some of the existing indices such as the NDVI analysis is insignificant relationships with BSC cover, and also they do not show significant relationships with other land covers, particularly with vascular plants percentage cover and perennial plants.

7-6-7. Capability of New Indices for BSC Detection

Eight newly developed indices statistically, particularly for the calibrated images, showed significant results for BSC, bare soil and total photosynthetic components in dry and wet conditions. Results of the "Dry season image" particularly are considerable with lower significance values when BSC were in dry conditions in comparison with two other images, when BSC were in wet conditions with higher significant values. Moreover, graphical results of the "Raw images" were not interpretable by considering the predefined hypothesis (7-4-5) as the highest cover value for the "Wet image", the "BSC image in the second level and finally the"Dry season image" with lower cover value. In contrast for all eight indices the sequence of positive or negative values for the three images supported the predefined hypothesis. Overall, from the results of newly developed indices, the three groups of indices can be classified. The first group has indices with positive values the same as the NDVI and SR (i.e. BSC_1, BSC_2 and BSC_3). The second group has indices with negative value the same as the SSI, but with similar gradient patterns to the vascular plants and BSC as derived from ground collected cover data in Sections 4-5-2, 4-5-3 and derived patterns from ground-level spectral modelling in Figure 6-7 (i.e. BSC_7). The third group has indices with positive value, but the gradient patterns are opposed to the "normal", "inverse", "composite" and "no gradient" patterns (2-7). In these indices the value of the index near water was higher than the sites away from water points (i.e. BSC_4, BSC_5, BSC_6 and BSC_8). As an example, there is support in the literature for the shape of gradient patterns for groups one and two, but the third group with an inverse gradient pattern to my knowledge is not supported by the literature and needs more investigation to conceptualize this form of index for rangeland condition interpretation or erosion / degradation estimation.

It has been generally presumed that most spectral information about biological elements can be derived from the visible- NIR and that water content masks most of the spectral features of live vascular plant material in the MIR and SWIR (Elvidge, 1990). The newly developed indices, BSC_7 and BSC_8 which are based on the MIR and other visible and NIR bands of TM imagery, had the best results in comparison with the indices based on the visible and NIR bands only. These findings need to be confirmed with follow-up studies that simultaneously measure visible NIR, MIR and SWIR field spectra for the BSC and other land covers, preferably with a spectrometer spanning the 400 -2400 nm range. This would build understanding of the relationship between visible NIR, MIR and SWIR spectral behaviour for arid environments under a range of conditions where BSC are common. Thus MIR and SWIR wavelength should be considered more in the development of an index or any kind of image analyses for BSC detection in chenopod shrublands of South Australia.

7-6-8. Standalone Remotely-sensed Methods for BSC Detection

From the results of the remote sensing of BSC in this Chapter, 12 candidate indices (Table 7-14), from the existing and newly developed indices for multispectral dataset such as Landsat TM, are proposed for a standalone remotely-sensed method. The main framework for utilizing these indices is restricted to the performed methods in this thesis, particularly stratification on the small paddock scale. From the results of stratification, indices should be tested on the shrubland communities. Standalone remotely-sensed method means utilizing candidate indices to selected images by defined criteria in this chapter, by a remote sensing concept such as: image selection; image pre-processing; image processing and randomly sample locations selection for spatial analysis by ground-truthing and accuracy assessment.

Table 7-14. Candidate indices for standalone remotely-sensed methods of BSC detection

Indices	Formulations
SSI	(Green /near infrared) – (Red / Near infrared)
BSCI	$1\text{-}L\times\lvert R_{red}-R_{green}\rvert / R^{mean}_{GRNIR}$
CI	1-(Red –Blue) / (Red + Blue)
NDVI	(Near infrared – Red) / (Near infrared + Red)
BSC_1	1 - (Red - Green) / (Red + Green)
BSC_2	1 - (Red - Green) / (Red + Blue)
BSC_3	2 - (Red / Nir) / (Green / Nir)
BSC_4	1 - (Green * Nir) / (Red * Nir)
BSC_5	(Red - Green) / ((Red + Green + Nir) /3)
BSC_6	(Green-Red) / (Green-Near Infrared)
BSC_7	(Green/Middle Infrared) – (Red/Middle Infrared)
BSC_8	(Green-Red) / (Green-Middle Infrared)

7-7. Conclusions

This chapter is based on the field collected data and image derived digital values by testing the existing indices such as the CI, BSCI, SSI, NDVI and SR, and by developing eight new indices as BSC_1 to BSC_8 for detecting and mapping the BSC distribution, employing its unique spectral features to illustrate some of the potential of multispectral imagery. Testing existing indices showed that the SSI, as soil stability index, is the best index from existing indices and BSCI and NDVI in the second level for detecting and mapping BSC cover. However, BSCI graphically and NDVI statistically have problems in detecting these components and need more investigation. The CI has low capability to detect BSC cover on lichen-dominated ecosystems such as those at MFC. Indices analysis in dry and wet conditions, and climatic analysis results showed that there is high possibility of misinterpretation of remotely-sensed data on the area in which BSC occur because of the heterogeneous rainfall patterns. Derived indices can be treated as an enhancement of spectral features of the BSC in green, red, NIR and MIR of TM imagery. Although, from the

numerical and graphical analyses, BSC_7 is the best index for BSC detection overall it cannot necessarily be concluded as the best index. This is because of the requirements of developed indices to apply to the detection of BSC to validate of them by a practical standalone study. This study developed these indices, but there was no chance to validate them as a standalone remotely-sensed method. This means developed indices need to be checked as a standalone remotely-sensed method of image interpretation and then accuracy assessment. Overall, by employing existing and newly developed indices, identification of BSC is impossible but a form of classification is applicable for BSC mapping. To sum up, BSC seem to be detectable using temporal-based remotely-sensed data, but moisture issues and effects of these on the soil, litter, stone and different BSC components, as well as the stability of moisture needs more experimentation in different seasons with different climatic situations to conclude the real impact of moisture effects on image interpretation. Overall, this thesis provides an introduction to index development for BSC detection in Australia. Most of the probable effective factors such as careful image selection, careful radiometric correction, moisture consideration, spectral characterization, and ground-level spectral modelling were considered. Although, some of the experiments for different reasons were not completed, most of the possible issues, which can be involved in BSC detection, were considered and in some cases, from the results of this study, direction for future studies is given.

CHAPTER 8

8. GENERAL DISCUSSION AND CONCLUSIONS

8-1. Synopsis of Rationale and Procedure

Land degradation is a current and future worldwide problem, particularly in arid rangelands (1-3 & 2-3). Methodologies of land degradation assessment are based on the evaluation of change in rangeland features such as vegetation cover over time (2-3 & 2-4). There are two groups of methods: ground-based and remotely-sensed methods for assessing rangeland condition (2-6). Both methods are based on a suite of indicators which are evaluated and monitored to determine the degree of rangeland degradation (1-3 & 2-3). Remotely-sensed methods have the advantages of time efficiency, broad coverage and repeatability over ground-based methods (2-6). Previous remotely-sensed methods have mainly been based on a limited set of indicators, particularly on vascular plant cover (1-3). There is an argument about the suitability and robustness of employed indicators and the possibility of adding more indicator(s) to remotely-sensed methods or an integration of ground-based and remotely-sensed methods (1-5). BSC is one of these indicators (1-7 & 2-5).

BSC provide a beneficial role in arid rangeland ecosystems, largely through the processes they mediate, in particular soil stability, nitrogen fixation, carbon balance, biomass production, micro relief, promotion of infiltration and prevention of erosion (1-6 & 2-5). Consequently, greater BSC cover might be expected to equate with a more stable and productive condition. Two BSC-based indicators, species composition and cover, have already been reported as important indicators of rangeland condition (1-6 & 2-5). There is strong agreement that BSC composition is a reliable indicator of rangeland condition. Although some studies noted that BSC cover is a response indicator of rangeland degradation, recent literature reported that BSC cover is a weak indicator (1-1, 1-13 & 2-6-2). Piosphere or grazing gradient provides the key to separate grazing pressure-induced effects in the landscape from those due to other factors (1-9 & 2-7). This study was conducted within a piosphere framework by five replications (paddocks) with sites located at various distances from water to examine sheep-based grazing gradients. This study employed various assessment considerations such as: suitable method selection; landscape stratification; landscape and site characterization, and BSC group classification. Classified BSC groups were sampled using a 100 m line-intercept method on the stratified units at different distances from water points. This study, initially using ground-based methods, examined the significance of BSC cover as an indicator of rangeland condition in the framework of piosphere.

Despite the widespread distribution of BSC in different parts of the world (2-5), and advantages of remotely-sensed methods (2-6), there have been few attempts to use remotely-sensed data for BSC monitoring (1-15). These limited studies were conducted in Israel for ground-level spectral analysis (1-15). A few studies were conducted for BSC mapping and in other studies BSC was one of the components in land cover mapping (1-15). Overall, there are many unknown issues, particularly in the response of species and BSC groups in monitoring of ground-based and remotely-sensed methods. Similarly, there is little knowledge about the regional spectral characteristics and remote sensing of BSC, particularly in Australia.

In this thesis remote sensing of BSC was conducted by spectral collection in the laboratory and the field using a handheld spectrometer in the visible and NIR regions (350-1100 nm) of the electromagnetic radiation spectrum. Spectral characterization was conducted for multispectral datasets such as Landsat TM imagery and commonly used indices such as the NDVI, SSI and PD54 in dry and wet conditions. Collected land covers data and spectra were used for ground-level spectral analyses to model the effects of BSC on a remotely-sensed method in the framework of piospheres. As a final and third stage, TM imagery was used to test the existing indices. Images were selected based on phenological stages of BSC, annuals and perennials. These images where then used to develop eight new indices for BSC detection. Because of the volume of this thesis, at this stage there was no opportunity to examine the newly developed indices in a standalone remotely-sensed method and it was therefore not possible to absolutely conclude which one of these indices was the best.

8-2. Synthesis of Main Findings of the Thesis

Taken together, the survey design, analysis and results of Chapters 3 to 7 develop both the understanding and problems of the ground-based and remotely-sensed methods for BSC cover monitoring. While each part (ground-based and remotely-sensed methods) examined particular issues in relation to BSC cover monitoring and explored the analytical approaches, there are several common themes and concepts for both methods. Viewed together, these hopefully motivate further examination of these methods in monitoring procedures. Findings of the thesis for defined questions in Chapter 1 can be summarized and discussed as:

8-2-1. Spatial Change in the Cover of BSC Related to Trampling (Grazing Pressure) that could be used as an Indicator of Rangeland Condition (Ground-based Assessment of BSC)

The first question of the thesis was; "Does BSC cover change significantly in the framework of the piosphere?" For the examination of BSC cover change in the context of piosphere some pre-consideration such as a suitable method selection; stratification and site characterization to

discriminate environmental variation from management affects; and BSC classification were required before variance analysis.

Therefore, prior to BSC cover variance analysis three ground-based methods for their suitability for chenopod shrubland communities were examined (Ch.3). Of the three methods, line-intercept (LIM100m) had the most consistent results and was used in this study (Ch.3). However, time allocation, labour intensity and cost for this method are of major concern. From time, labour and cost perspectives, with more investigation, the point intercept method could be a suitable surrogate for the line-intercept method, particularly for remote sensing of large areas. Strata were defined from an initial field visit, visual interpretation of TM imagery and field checking to define sample locations. Shrubland communities were selected as the first priority for sample locations, because of their high relationships with BSC cover (Ch.3). Forty four percent of the sites were selected in this community. Sufficient sites for replication could not be located within this stratum, so the second priorities were shrub-woodland and wood-shrubland communities with 43% of the sites selected on these communities (Ch.3). Finally, 13% of the sites were selected on woodland communities with weak relationships with BSC distribution (Ch.3). From the literature (Rogers & Lange, 1972; Eldridge, 1998b; Eldridge, 2001) and results of this study (Ch.3) negative relationships exist between sandy soil and BSC distribution. Therefore, attempts were made to avoid site selection on sandy soils. As some literature (Johansen, 1993; Hawkes & Flechtner, 2002) pointed out, pH is important for BSC distribution and acidic soil (pH 4.2 to 5.2) causes specific distribution of communities with the dominance of cyanobacteria and diatom components. However, at MFC pH in all sites are alkaline, and lichens and mosses are dominant. According to the alkaline range of pH it seems that it is not an effective factor for BSC spatial change in the study paddocks at the different sites. Other landforms, i.e. crests and watercourses, were avoided for sampling site selection (Ch.3). Soil patches with a distribution in 20% of the sites showed negative relationships with BSC distribution. Nonetheless, landscape stratification did not remove all environmental variations and was not 100% successful, thus in some sites cover of BSC was related to secondary environmental variables rather than management (grazing "trampling" pressure) variables. Six BSC groups were defined as suitable classes for data collection. Classified groups, particularly Scaly, Crusty, Leafy Lichens are similar to Eldridge and Rosentreter's (1999) classification; however, the Black Common Lichen group is a complex group in comparison with their classification. Moreover, mosses in comparison with Eldridge and Rosentreter (1999) are classified in two groups. MFC is a lichen-dominated rangeland with 79% of total BSC cover. Black Common Lichens (62%), Black Common Mosses (20%) and Scaly Lichens (13%) are the

dominant BSC groups. On the other hand, Leafy Lichens (2.84%), Crusty Lichens (1.90%) and Tall Mosses (0.45%) have comparatively low cover.

Cover of different BSC by stratified sampling were statistically analysed to test the significance of their cover change in the framework of piosphere. Overall, there is little investigation of BSC cover as a measure of rangeland condition at the regional scale in different parts of the world and most of the conducted studies have been at small scales, such as the comparison of inside and outside of exclosures (Kleiner & Harper, 1977; Anderson *et al.*, 1982; Klopatek, 1992) and only one at a broad scale by Eldridge and Koen (1998). My results support the results of Klopatek (1992) and Anderson *et al.* (1982) who concluded that BSC cover are a significant indicator of rangeland condition. However, my results contrast with those of Eldridge and Koen (1998), who concluded that BSC cover is a weak indicator. Eldridge and Koen (1998) used small quadrats for their data collection. However, from my results the quadrat method had the highest sampling variation compared to the line-intercept and point intercept methods. Moreover, strong relationships exist between soil and vegetation patchiness with BSC distribution (Eldridge, 2001). Stratification is a proposed method to remove or reduce the "noise" effect of these kinds of variations (Ludwig & Tongway, 1992; Belnap *et al.*, 2001b). There is no evidence of stratification in Eldridge and Koen's (1998) study which was conducted on two soil types. My study area is also distributed on two soil types (3-2-3); however, the results of stratification show that each of these could potentially form a heterogeneous mosaic of soil sub-types and affect the BSC distribution. It should be noted that this study was based on total BSC and morphological /functional group level, and species cover variation was not included because of complex taxonomy and field identification problems. By considering the soil productivity potential, BSC at 100 m sites from water have lost 20 to 30% of their potential cover. All cover components of BSC except Tall Mosses, showed a significant relationship with distance from water by inference with grazing pressure (trampling). Thus BSC cover is a significant indicator of grazing pressure. Lichens are more sensitive than the moss components as an indicator. Between the lichens, Crusty and Leafy Lichens are more sensitive than the other lichens as an indicator of rangeland condition.

8-2-2. Remote Sensing of BSC

The capability of remotely-sensed data to detect and map the distribution of BSC offers the opportunity to extend site specific ecological studies of crusts to a regional scale, thus reducing the time and costs associated with ground-based studies (Karnieli *et al.*, 2001). The distribution and percentage cover of BSC at MFC, which varies from 1.69 to 36.99% (4-5-3), potentially could have considerable affect on the remote sensing signals compared to vascular plants with 8

to 36% of cover (Appendix C-1). Annual plants, with their short growing period characteristic and cover of 0 to 16% (Appendix C-1), have a low contribution in the overall signals of remotely-sensed data from the collected data for the study years by comparison; however their contribution in "wet years" could be considerable. From the existing information and capability of current technologies, direct measurement "identification" of BSC is impossible even using high spatial and hyperspectral remote sensing. This is because of the size and biophysical variations of these components. As Karnieli (2003) and Burgheimer *et al.* (2006a) concluded, a temporally-based remote sensing method could be used to detect the quick response of BSC to a rainfall pulse in comparison with annuals and perennials. This is because of the nature of BSC—which are poikilohydrous— responding quickly to moisture and changing from dormant mode to an active mode, however the duration of this period depends on the different climate components (Chs. 6 & 7). Thus a reliable remotely-sensed method of BSC detection should consider variables such as rainfall, temperature and evaporation to derive the possible phenological patterns (7-4-2), moisture, and dehydration patterns (6-5-4) for a given study area. Moreover, understanding vascular plant communities and soil characteristics (Chs.3 and 4) is also important in the context of pixel level. Therefore by considering these issues and defined questions in Chapter 1, remote sensing of BSC can be summarized and discussed as:

8-2-2-1. BSC Spectral and Indices Characteristics in Dry and Wet Conditions in Comparison with Other Land Covers

The thesis aims were to evaluate whether significant differences exist between the spectral signatures of BSC and other land covers (vascular plants, bare soil, litter and shadow) with different amounts of moisture at different times of the year. Very large spectral variations and complexities exist within and between different land covers at MFC. Overall, results from ground-level spectral characterization can be summarized and discussed based on two sub-questions: spectral characteristics of BSC and other land covers to understand and conceptualize remotely-sensed methods (i.e. similarity between individual BSC groups; similarity between the individual BSC groups and other land covers; similarity between "BSC pattern spectra" and other land covers); and existing indices' suitability for BSC detection from ground collected spectra such as the PD54, SSI and NDVI.

Spectral Characteristics of BSC and Other Land Covers to Understand and Conceptualize Remotely-sensed Methods

Within the individual BSC groups colour and greenness are important characteristics of different BSC components from a remote sensing perspective. Plotted spectra for six groups showed that

two main super groups can be classified. The first super group including Black Common Lichens, Black Common Mosses and Tall Mosses (82%) exhibit low brightness values, in comparison with the second super group including Scaly, Crusty and Leafy Lichens (18%) with higher brightness values. Black Common Lichens (62%) from the first super group have some similarities in visible wavelength with moss components, however in NIR regions brightness value and pattern are different from the mosses. Although Black Common Mosses (20%) and Tall Mosses (0.45%) have similar brightness and patterns in dry conditions, in wet conditions their differences increase, particularly in the "red edge" region. Although the second super group has higher brightness value, they have different patterns from each other. In wet conditions the brightness value for the three groups of the second super group is high, but some changes in the spectral patterns, particularly in the "red edge" region occur. Spectral patterns in the data space of band 3 versus 2 of TM imagery showed promising results with almost the same spectral patterns for each BSC group of the first super group in dry and wet conditions, however Scaly, Leafy and Crusty Lichens in comparison showed broad distribution of spectra and low success in this regard.

Spectra of BSC are different from other land covers in dry and wet conditions. However, in certain wavelengths, particularly for a synthesized TM-like dataset, similarity exists between BSC and other land covers in dry and wet conditions. These similarities in the visible regions between dark colour BSC, and litter and shadow are very high. In contrast very low similarity exists between Leafy, Crusty and Scaly Lichens with shadow and litter data in dry and wet conditions. The possible misinterpretation between BSC groups and vascular plants can occur between annual and perennial herbages, and Leafy lichens. Moreover some similarities exist between woody species with dark colour BSC in dry and wet conditions. The individual BSC group level results of this thesis, in comparison with bare soil, support O'Neill's (1994b) results that differences exist between the soil and BSC spectra in Australia.

From a remote sensing perspective, particularly for multispectral imagery, plot spectra (BSC pattern spectra) are more important than the individual BSC for land cover classification. My results showed that differences exist between the brightness values of "BSC pattern spectra" and bare soil. However, the general pattern of the spectra and index values for bare soil and "BSC pattern spectra" in dry conditions are similar and support the results of the Negev desert studies (Karnieli & Sarafis, 1996; Karnieli *et al.*, 1996). In wet conditions brightness values are reduced and general spectral patterns were less similar to bare soil and supports the results of O'Neill's (1994b) study (in Australia) and studies in Israel (Karnieli *et al.*, 1999; Karnieli, 2003; Burgheimer *et al.*, 2006a) that differences exist between the spectra of wet "BSC pattern spectra" and bare soil. My results were in contrast with those of Lewis *et al.* (2001) and Fildes' (2005)

studies who included all BSC components as one or two groups. If they used spectral patterns of BSC components as one endmember, there is a difference between actual cover and BSC as one group (6-5-3). Alternatively, if they used a group of BSC as one endmember, the question arises about the other groups with different spectral patterns and similarities with litter, shadow, bare soil and vascular plants, particularly in dry conditions.

Overall, from the results of spectral analyses that can assist in the detection of BSC, individual spectra has a different spectral pattern from the bare soil in dry and wet conditions, but in dry condition "BSC pattern spectra" has a similar spectral pattern to bare soil. In the wet conditions individual and "BSC pattern spectra" are different from the bare soil, but in both dry and wet conditions the main overlap and similarity exist between the litter, shadow and vascular plants with BSC groups, particularly in the visible region and between the data space of band 3 versus band 2.

Effects of Dry and Wet BSC on the Indices-based Remotely-sensed Methods such as the PD54, NDVI and SSI

The PD54 is one of the commonly used indices in Australia (Chs. 2 & 5). It is widely used for rangeland monitoring and is concluded as the most suitable index for the Australian arid rangelands (Bastin *et al.*, 1993a; Pickup *et al.*, 1994; Pickup & Chewings, 1994; Bastin *et al.*, 1998; Brook *et al.*, 2001). There is ongoing use of it in areas where BSC are widespread (Cameron & Lewis, 1996; Clarke, 2004). Extensive individual BSC spectra showed that these components have no affect on the soil and vegetation lines in dry and wet conditions. Moreover, although the "BSC pattern spectra" have different brightness values they have similar patterns to bare soil in the data space of band 3 versus band 2 of TM imagery, where PD54 is based on this data space. However, there is no affect of "BSC pattern spectra" on the vegetation and soil lines. Therefore neither individual BSC nor "BSC pattern spectra" affects the vegetation and soil lines, and these lines are determined by bare soil and vascular plant spectra. Thus, employing the PD54 in an area where BSC are widespread may create bias in the results of a remotely-sensed method. In short, this index has little capability to discriminate an area with 1.69% of BSC cover from an area with 36.99% at different distances from water points. In both cases index values are defined with bare soil and vascular plants. Thus in the image interpretation by this index, the value of BSC are neglected by this inefficiency. Results of the NDVI analysis showed some similarities between the individual BSC groups and species with bare soil, stone, litter, vascular plants and shadow data in both dry and wet conditions, thus there could be possible misinterpretation between BSC and these components. There are some promising results, such as the distinguishable patterns for mosses and different spectral values among the bare soil and BSC

components using the SSI for BSC detection, highlighting that the SSI seems to have potential to apply on the area in which BSC are common.

8-2-2-2. Modeling the Effects of BSC on the Grazing Gradient Patterns Using Ground-level Spectra and Possibility of Image Selection for BSC Detection

In order to understand how BSC spectra affect the cover estimation in rangeland monitoring in dry and wet conditions, five sub-questions are defined in Chapter 1, which can be summarized and discussed as:

Index Value Differences for Varying BSC in Dry and Wet Conditions

At the species level, index value variations are very high from species to species, thus it can create potential for remote sensing of these components when images are selected in wet versus dry conditions. In the groups level for the NDVI and SSI, although the similarities between BSC groups are increased, the differences between dry to wet conditions are still considerably high and support the idea of image selection based on dry versus wet conditions to detect the greenness value change when other biological elements such as annuals and perennials are inactive.

Index Value Differences between BSC and Other Land Covers in Dry and Wet Conditions

NDVI value similarities in dry and wet conditions for some of the BSC components with bare soil, litter, stone, shadow and vascular plants are considerable and support the results in the Negev desert (Karnieli & Sarafis, 1996; Karnieli *et al.*, 1996; Karnieli *et al.*, 1999; Karnieli, 2003), thus there could be possible misinterpretation using the NDVI between BSC and these components. Misinterpretation could be more considerable if single image selection in dry conditions of BSC is considered. However, for the SSI, these similarities are small, thus probably there would be the potential for using this index in dry or wet conditions for BSC detection. NDVI and SSI value changes from dry to wet conditions for BSC components are large in comparison with bare soil, litter and stone. Thus, these differences create a possible potential for image selection based on dry versus wet conditions for BSC detection when annuals and perennials are not yet active. Although the amount of index value change for bare soil, litter and stone in comparison with BSC is small, this small change can affect the overall results of a remotely-sensed method, thus caution should be exercised with image selection.

The Spectral Differences Between Surfaces (Plot) Covered With and Without BSC

Results of this study for pattern (plot) analyses showed that differences exist between the NDVI values derived from one species and the spectra of a complex BSC group with bare soil background. Results of this thesis show that there are small NDVI value differences between the dry conditions for area covered with BSC in comparison with the area without BSC, and support the results in the Negev desert (Karnieli & Sarafis, 1996; Karnieli *et al.*, 1996; Karnieli *et al.*, 1999) in dry conditions. Thus, there is the high possibility of misinterpretation of BSC as bare soil and vice versa in dry conditions. It should be noted that almost all of the studies conducted on the areas in which BSC are common, in order to avoid moisture content have selected their imagery in dry conditions (Cameron, 1995; Lewis, 1998; Lewis, 2000; Lewis *et al.*, 2001; Lewis, 2002b; Fildes, 2005). By contrast, in wet conditions, the similarity between bare soil and BSC is large and results support O'Neill's (1994b) and others' (Karnieli *et al.*, 1999; Karnieli, 2003) that there are different spectral values in wet conditions, even with bare soil background. Thus, there is the possibility of detecting BSC in wet conditions, however the level of moisture is an issue and should be considered more.

The Possible Spectral Models to Evaluate Grazing Gradient Patterns With and Without BSC

Five possible models using spectra were examined. These spectrally derived grazing gradient patterns (models) with and without BSC are considerably different. A conditional state (model 5/ Ch.6) for BSC detection is developed based on the wet spectra of BSC and dry spectra of bare soil, litter and stone. However, much depends on the moisture stability of different land covers. Therefore, if image interpretation such as that of Lewis's (1998) study does not take BSC components into account during cover estimation, then misinterpretation and bias could result. Distinguishable differences exist between the models derived from BSC as one group versus models which used different BSC groups. Thus, single group selection, such as those of Lewis *et al.*'s (2001) study who selected all BSC components as one endmember, will create biased results in the cover estimation as lower cover value for a study area. The problem with a single group model could be more distinguishable if grazing gradient patterns were considered as "normal", "composite", "inverse" or "no gradient" (2-7), as misinterpretation of rangeland condition by different models. More importantly, if interpreters use the estimated cover for a secondary analysis such as soil erosion estimation the results by different models could be completely different.

The Temporal Changes in Spectra as a Function of Changes in the Moisture

Time to dehydration stage is a crucial variable for using remotely-sensed data to detect BSC. Dehydration depends on the temperature, moisture, humidity and maybe some other factors. All rangeland features after a rainfall pulse will be affected by moisture. Litter and stone dehydrate in a short period in comparison with bare soil, which, in turn, has a shorter period of dehydration than BSC. In spring and summer temperatures are high (35-40°C) and litter, soil, stone and BSC all dehydrate after less than 4 to 5 hours (maximum one day). It is therefore difficult to select an image from spring-summer to detect BSC. However, in the early spring, late autumn and winter the window of opportunity for image selection will increase to 2 to 4 days after an influence rainfall pulse (>10 mm), because dehydration periods are much longer than in the hotter periods of the year. Overall, from the results of spectral analyses of moisture stability, there is a potential for selecting an image based on the dry soil, litter, stone and wet BSC when annual and perennial plants have not yet started to grow (model 5 / Ch.6). In spite of an unclear pattern for the SSI, there was a clear moisture pattern for the NDVI. Karnieli's (2003) study in Israel has also shown that there is a possibility of image selection based on the BSC growth stage to use remote sensing data. However, the main concern is the moisture stability for bare soil, litter and stone in comparison with BSC. By considering the limited field and laboratory experiments conceptually there is a possibility of selecting an image in late autumn (May to early June) in the second or third days after an influential rainfall pulse to obtain the greenness values of BSC. Autumn experiments were conducted in 30°C, thus rationally there is an expectation that in the period with maximum 20°C temperature, the continuity of greenness for BSC, and higher moisture level for bare soil, litter and stone increases. Alternatively, if an image is selected in late August or early September after 2 to 4 days of a rainfall pulse, BSC greenness value will be included in the overall cover value. The results are not completely clear and need further investigation in the field on a monthly base with spectra collection to model the real extent of the period of dehydration for bare soil, litter, stone and BSC. Reviewed literature in Israel mostly compared dry spectra versus wet conditions of different components. Thus, with limited information about the soil, stone, litter and BSC moisture stability after a rainfall pulse in different seasons and different conditions, it is difficult to conclude the real extent of moisture stability in mentioned components. Karnieli (2003) reported that the beginning of the wet season is suitable for BSC detection, however, he did not cover the duration or moisture stability and biological activities of BSC after a rainfall pulse and did not compare this for other rangeland features.

8-2-2-3. The Possibility of Using Multispectral Datasets for BSC Detection

The possibility of using Multispectral Datasets was based on image selection and BSC detection.

The Most Appropriate Times for Image Selection for BSC Detection

This study is based on the climatic data analysis of the study years and phenological records during the study period only. Annuals start to grow from early to mid June and die off in early September. There is limited annual growth in the rest of the year. After a rainfall pulse BSC responds immediately; however in hot seasons the period of BSC growth is short and it is impossible to select image(s) based on this stage, except a possibly in "wet years". Most of the perennials at MFC are not deciduous plants, however there are discernable growth stages for this group from mid to late June until at mid to late October. Overall, by considering the rainfall pattern during the study years and phenological stages, there is a possibility to select an image in early June before annuals and perennials start to grow for the detection of BSC after a rainfall pulse (maximum 2 to 4 days). The period between the commencement of annual and perennial growth is short when compared with observations of the Negev desert phenological patterns. Karnieli (2003) claimed that there is a distinguishable period (about 4 weeks) in the Negev desert between annual and perennial growth. Because of the temporally-close response of annual and perennial growth at MFC, it is difficult to select an image for the annual growth stage. However, almost all annuals dried in late September and after this month a selected image will not include a significant spectral contribution from annuals. Finally, an image selected after a rainfall pulse in late August can estimate the cover of annuals, perennials and BSC.

It should be noted that results of the study years can not be applied for the other years, because of the climatic variations, thus the question will arise, what is the benefit of a one year BSC monitoring? Yearly BSC cover evaluation using remote sensing data can help to define rangeland condition using time series imagery for rangeland trend. Rainfall and climatic components in the Australian outback are unpredictable and vary from year to year (Stafford Smith & Morton, 1990). Perennials and annuals can be affected as the amount of cover change by these varies from year to year (Foran, 1987; Pickup, 1989; Stafford Smith & Morton, 1990). Therefore, they are less reliable indicators for temporally-based remotely-sensed studies for rangeland condition and trend analysis. However, BSC in comparison are less affected by climatic variations and change in the amount of their cover from year to year. As concluded, they are sensitive to trampling and in the framework of piosphere they have demonstrated significant changes under grazing pressure (trampling) (Ch. 4). Thus using time series images (with the intervals of 10 or 20 years), we can determine the amount of change in a given site by judging the amount of change in the BSC cover (Ch. 7). For this procedure, the amount of annual and perennial plants should be known for the selected image time. Overall in the framework of piosphere in a given year there is the possibility of selecting remotely-sensed data for BSC

monitoring, however from this study the issues of moisture effects on soil, litter, BSC and dehydration stage for each component is of concern and needs more investigation.

Moreover in the use of remotely-sensed methods on the areas in which BSC are common, it should be noted that an area such as the MFC-Whyalla region does not exhibit spatially homogeneous rainfall patterns. In the same year in Whyalla with proximity to the sea and in MFC, Roopena and Iron Knob, with 20 to 40 km distances, there were high variations from the amount and number of rainy days, which is an important factor in the image selection stage. Selected images after a small rainfall (1 to 2 mm), for example in Whyalla, can cause growth of BSC and change the spectral value, however 20 to 40 km away in MFC, Roopena and Iron Knob BSC could be dry and spectra for the same pattern of BSC could be different. It is important to consider the daily weather (rainfall events) both temporally and spatially in the areas in which BSC are common, particularly when using coarse scale images such as the MODIS or NOAA AVHRR. A high probability exists for a selected image in large areas with a rainfall pattern such as Whyalla-MFC region, to contain different spectral values and misinterpretation for the same BSC community. Thus, it is important to select remotely-sensed data by taking into account the timing and distribution of daily rainfall data using spatial division methods such as the Thiessen polygon (Appendix E-3) at each station for each rainfall event.

The Possibility of Detecting BSC Using Existing or New Indices Derived from Multispectral Remote Sensing

Two developed indices for BSC detection, the CI and BSCI, have not shown significant and reliable results (BSCI statistically is significant but graphically has problems) for MFC. The CI was developed on a cyanobacteria-dominated area and considerable differences exist between the spectra of a cyanobacteria-dominated area (Karnieli, 1997) and lichen-dominated rangeland. Chen *et al.* (2005) concluded that the BSCI could be sensitive if BSC cover is more than 33%, however at MFC 22 out of 30 sites had less than 33%. Moreover, in their study area there was a distribution of algae with quite different spectral patterns to those at MFC (Ch.5). Some other indices, such as the NDVI, which are extensively used throughout the world including Australia, showed large changes for ground-level spectra for different components from dry to wet conditions, however for image data graphical results showed high similarity with ground collected data and ground-level spectral models of grazing gradients. However the NDVI statistically was not significant, supporting the claims of the literature (Quattrochi *et al.*, 1997; Goodin & Henebry, 2002) that there is difficulty in accurately transferring models between field and satellite scales in a linear fashion. The SSI had the best results among the existing indices and showed some promising results for detecting BSC using image data. Although there were

some uncertainties for ground-level spectral modeling in wet conditions (Ch. 6), overall results for the SSI (derived gradient models) support the NDVI and ground collected data.

Eight new indices were developed from TM imagery and collected cover data from pre defined sample locations, which had significant results with the ground-collected BSC cover. From those, indices based on the MIR in combination with other visible and NIR wavebands had the best results for BSC monitoring. Other indices also had significant results ($p>0.05$ & $p>0.01$); however within this study there was no opportunity to test the developed indices by a standalone remotely-sensed method. Therefore, these new indices need to be tested for validation to conclude the best index for BSC detection in shrubland communities at MFC. Because of the similarity of shadow and BSC data, sun standardization and shadow consideration is a critical stage in monitoring BSC remotely.

8-2-2-4. Overall Potentials and Limitations of Remotely-Sensed Data for BSC Detection

Overall, in remote sensing of BSC, the problem is to identify the presence of the BSC in a large-scale exposure of soil, where bare soil could produce a similar response and identification of these components. Understanding the nature and extent of the biological components, including the BSC spectral contribution, is important, not only for ecological applications where the biological components is of primary interest, but also for soil and geological studies where the biological components may confound interpretation. Multispectral imagery has already demonstrated its strength in discriminating and mapping biophysical variables (biomass, Leaf Area Index and cover) and in monitoring vegetation condition (i.e. greenness), but discriminating variations in biological components has proven to be difficult (Lewis *et al.*, 2001; Fildes, 2005). The existing multispectral sensors are inherently limited for the discrimination of different species and variations in biological composition because of their broad wavebands, the limited number of spectral bands, and their moderate to coarse spatial resolutions. However, temporal evaluation of land covers including BSC, according to the discussed procedures in this thesis, is possible but many issues are involved in this mixed process and more consideration is required.

Increasing the spatial resolution of the instrument would not increase the likelihood of mapping the presence of BSC against a background of soil or vascular plants, unless the spatial resolution approached that of the individual BSC colony size of a few centimetres. If the spatial resolution approached that of a small BSC colony size (2-3 cm), individual BSC morphologies could be resolved and the distribution of a specific BSC could potentially be mapped using this criteria. High spatial resolution data, colour photography for example, could possibly resolve the problem of BSC detection, if their spatial resolutions reach a centimetre level. Despain (1990) used crown shapes in colour aerial photographs to map trees in Yellowstone National Park, but

even bushes and grasses were too small to resolve the structural detail related to species. Thenkabail *et al.* (2003) used IKONOS and Landsat ETM+ images for detecting floristic structure and pattern across topographic and moisture gradients in a mixed species pattern in central Africa, with the claim of significant results for floristic structure mapping, but not individual species discrimination. McGlynn and Okin (2006) used high spatial resolution remote sensing for investigating shrub distribution. They classified shrub distribution and shrub encroachment, but could not discriminate shrub species using high spatial remote sensing, thus mapping BSC seems impossible by the use of existing high spatial resolution data. Finally, maybe some *in situ* verification using very high spatial resolution dataset such as IKONOS, QuickBird or aerial photography could resolve spatial components of BSC.

Airborne hyperspectral remote sensing, however, offers considerable potential for discrimination of earth surface materials because of its high spectral resolution and its associated high spatial resolution (Lewis *et al.*, 2001; Okin *et al.*, 2001b; Clark *et al.*, 2005; Fildes, 2005). Hyperspectral imagery has been used successfully for detection and mapping of minerals and soils, and discriminating crop types and conditions, while most work in natural biological components has been in North America and other grassland, woodland and forest (Treitz & Howarth, 1999; Lewis *et al.*, 2001; Schmidt & Skidmore, 2003; Ben-Dor *et al.*, 2004; Arsenault & Bonn, 2005; Clark *et al.*, 2005; Fildes, 2005; Glenn *et al.*, 2005). Main land covers (soil, rock, litter and vascular plant) variation on arid rangeland ecosystems are potential mixture sources (Okin *et al.*, 2001b) with BSC. For example, Lewis *et al.*(2001) and Fildes (2005) claimed that several biophysical components including BSC as one or two endmembers were successfully mapped using the automated mixture of Airborne Multispectral Scanner and HyMap imagery in southern Australia. Clark *et al.* (2005) claimed that they could successfully map species level classification of individual tree crowns in a tropical rainfall forest using high spatial and hyperspectral resolution imagery. Thus according to this literature, the most suitable remote sensing tool for BSC detection is hyperspectral remote sensing based on the classified groups or a spectrally-based classification which may provide a possibility of remote classification of these components. Consequently, when using the current remote sensing technologies, spectral and temporal resolutions are more important than spatial resolution for mapping BSC cover. Because of the moisture responses of BSC in a short period, high temporal-spectrally based remotely-sensed data such as Airborne Multispectral Scanner are more useful than space borne remotely-sensed data with constant temporal resolution for BSC detection.

8-3. Gaps in Knowledge and Future Research

A main gap in the literature highlighted by this investigation stems from the lack of preliminary considerations prior to data collection in BSC cover monitoring, particularly the use of stratification and the selection of a suitable method of ground-based data collection. Piosphere studies mostly measure the gradient using a number of variables, but only on one occasion and usually in dry conditions. Although simulation studies, such as those in this study, are able to predict the long-term piosphere dynamics of BSC, future work should be directed at validating these predictions, and relating changes in these gradients to changes directly to grazing (trampling) in animal pressure.

In the remote sensing section, only visible and NIR wavelengths are considered for spectral analysis, mostly for the multispectral dataset of TM imagery. The ground-level spectral modeling and image-based data analysis could be improved using hyperspectral, high spatial and high temporal resolution images such as Airborne Multispectral Scanner, HyMap, CASI, Hyperion, AVIRIS, IKONOS, QuickBird, ASTER, MODIS or high spatial and temporal resolution aerial photography. Overall, gaps in the knowledge and future studies suggested by this thesis in hierarchical order are:

1. There are strong relationships between BSC distribution, vascular plant communities, and soil and landscape components. Topographic information accurate to 5 to 10 m (Horizontal) and 1 to 2 m (vertical) on flat land systems such as this study, and use of object-based image analysis (eCognition, 2004; Feature Analyst, 2005) using high spatial remote sensing data such as IKONOS or QuickBird could facilitate stratification and site characterization for BSC detection. However, the cost of imagery for low economic value ecosystems could be of concern. Moreover, ground-truthing of even object-based procedure is also a main concern.
2. There is the possibility of a BSC group classification based on spectral characterizations. This study tests the results of classified BSC groups using a synthesized multispectral dataset but only in the two-dimensional data space of band 3 versus band 2 of TM imagery. A more precise test of BSC group classification using principal component analysis (Kendall, 1975; McGarigal *et al.*, 2000) and discriminate analysis (Klecka, 1980; McGarigal *et al.*, 2000) of the hyperspectral data, collected by spectrometer, could more accurately assess the accuracy of classified groups for multispectral and hyperspectral remote sensing.
3. The choice of a method for ground-based data collection is a critical factor in the results of BSC monitoring. This thesis shows that the difference between the employed methods was considerable. Thus basic research on method comparisons for each BSC bioregion in

Australia could be useful to find a suitable method of ground-based data collection and ground-truthing of remotely-sensed methods.

4. A comprehensive meteorological study is required into the suitability of existing meteorological synoptic, climatology and rainfall stations for more precise conclusive climatic study for deriving phenological patterns. Furthermore, there is a requirement for long-term phenological records, at least 20 years, using the link with the Australian "BioWatch Project" (Rice, 2004) for chenopod biological components to model the BSC and other components precisely.

5. BSC seem to be detectable using temporal images of multispectral data, but the effects of moisture on the signal of soil, litter, stone and BSC needs more research to conclude more precise effects on image interpretation. At least 12 experiments (one for each month) such as in the study by Burgheimer *et al.* (2006a), under field condition are required to deduce the real extent of the effects of moisture stability and phenological patterns on BSC detection by remote sensing. A study such as the one differentiating rice from other crops by moisture content (Van Niel *et al.*, 2003) might provide a useful model for similar research on BSC.

6. There are some difficulties such as sun elevation, sun angle and shadow effects in remote sensing of BSC. Converting data to exoatmospheric reflectance based on the existing information and techniques is fraught with issues and a more precise radiometric and atmospheric calibration method is required for remote sensing and index development for BSC detection. The newly developed indices in this thesis are characterized for shrub-dominated rangelands and need to be standardized by a standalone remote sensing method. This means testing the newly developed indices using a standard remotely-sensed method involving image selection, calibration, image interpretation and the use of randomly selected sample locations for ground-truthing and accuracy assessment. There is the possibility of introducing systematic errors when taking an index developed from a shrubland community and applying it in other vegetation communities. So there is a need to recalibrate and characterize each index before this is undertaken.

7. Potentials and limitations of existing remote sensing technologies concluded that high temporal-spectral resolution is more suitable for BSC detection. From high temporal and hyperspectral data airborne technologies such as CASI, Airborne Multispectral Scanner are suitable to use in an organized image acquisition procedure for a defined period in cold seasons before and after an influence rainfall pulse (based on the greenness of BSC after dehydration of litter, soil and stone). A third image can be based on the peak growth stage of annuals, perennials and BSC after a considerable rainfall (based on the greenness of

BSC, annuals and perennials after dehydration of litter, soil and stone) for comparison. For the mentioned high temporal and hyperspectral imagery spectral unmixing (Smith *et al.*, 1990; Lewis *et al.*, 2001; Okin *et al.*, 2001b; Asner & Heidebrecht, 2002; Fildes, 2005) could be a reliable method for separating land cover variation on the mixed patterns of rangeland ecosystems. Although the size and BSC pattern with background soil could still be a main concern.

8-4. Conclusions

Results of this thesis, by considering a suitable method selection, stratification and site characterization, and morphological / functional group classification, show that there is indeed a direct relationship between distance from watering points and the percentage cover of total BSC (lichens, mosses, Black Common Lichens, Black Common Mosses, Scaly Lichens, Leafy Lichens and Crusty Lichens) suggesting that these can be used as an indicator of rangeland condition. However, Tall Mosses with 0.45% cover are the only group which did not show significant relationship with trampling.

Results of spectral analyses showed that there are different spectral characteristics for different classes of BSC from pattern and brightness perspectives. BSC components in dry conditions with individual spectral characteristics have different spectra from bare soil, however "BSC pattern spectra" in dry conditions from a spectral pattern perspective and index value point of view are similar to bare soil. In wet conditions individual BSC components and "BSC pattern spectra" are different from bare soil. There are high similarities between BSC spectra with litter, shadow, and vascular plants in dry and wet conditions. There are no effects of individual BSC and "pattern spectra" on the soil and vegetation lines of band 3 versus band 2 of TM imagery. The PD54 is not a suitable index for an area in which BSC are common, however indices such as the SSI are suitable.

Results of ground-level spectral modelling for grazing gradient identification showed that there is indeed a distinguishable effect of BSC in the results of the NDVI and SSI. Five possible models of grazing gradient model were examined to derive the effects of BSC in remotely-sensed data. There is a distinguishable grazing gradient pattern with and without BSC consideration. A scenario for detecting BSC was derived for the wet (after rainfall) conditions of BSC, when litter, stone and bare soil were dry. Two to four days after a rainfall pulse in late autumn, winter and early spring are suitable times for image selection for BSC detection by considering the study years' data. If BSC components are considered as one group in the image interpretation, results could be biased as low cover estimation and rangeland degradation,

misinterpretation of hydrological balances, erosion, and biomass of estimated cover would be used for secondary analysis.

This study is based on the climate/weather data of the study years and almost two years of phenological observations. BSC respond immediately to moisture at any time of the year, however in late spring, summer and early autumn there is no possibility for image selection according to temperature limitations. In winter, before annuals and perennials start to grow, after an influence rainfall (at least 10 mm) there is the possibility of image selection based on the BSC growth stage. Between annual and perennial growth there is no possibility of an image selection for annual detection, however in September all annuals dried and the selected image after September until early winter is representative of perennial plants (without rainfall events before an image selection / at least 10 days). A third image could be based on the period of peak annual, perennial and BSC growth stage in late August after a maximum 2 to 4 days of rainfall event (>10 mm). In image selection on the areas in which BSC are common, temporal and spatial distribution of rainfall is necessary to take into account for accurate image interpretation.

Results of image analyses for raw and calibrated images showed that from the existing indices the SSI is the best index, and BSCI and NDVI are at the second level. However, BSCI graphically and NDVI statistically have problems for BSC monitoring. The CI did not show significant relationships with BSC distribution. Eight new indices by a multispectral remote sensing data were developed for BSC detection. Although statistically the best results were achieved using a fraction of MIR, in combination with visible and NIR wavelengths, this study could not conclude which is the best index and a standalone remotely-sensed study is needed to conclude the most suitable.

These results are promising for application to rangeland monitoring and suggest that BSC cover is an important indicator of rangeland condition if appropriate stratification, classification and data-collection methods are used. Application of certain indices such as the PD54 may create mis-estimation of land covers. The effects of BSC cover on a remotely-sensed method are considerable, and thus they cannot be neglected during image interpretation. There are different phenological patterns for BSC, annuals and perennials, thus there is the possibility for the selection of imagery based on each phenological stage to detect these components. Although some of the existing and newly developed indices had significant results for BSC cover estimation, there is a requirement for a standalone remotely-sensed method to conclude the best index. Overall, BSC seem to be detectable, but moisture issues and effects on the soil, litter, stone and BSC and dehydration need more investigation in different seasons with different climatic conditions to conclude the extent of the moisture effects on the image interpretation.

Moreover, using high temporal and hyperspectral remotely-sensed data could be the next step for investigating the capability of these advanced technologies for BSC detection.

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APPENDICES

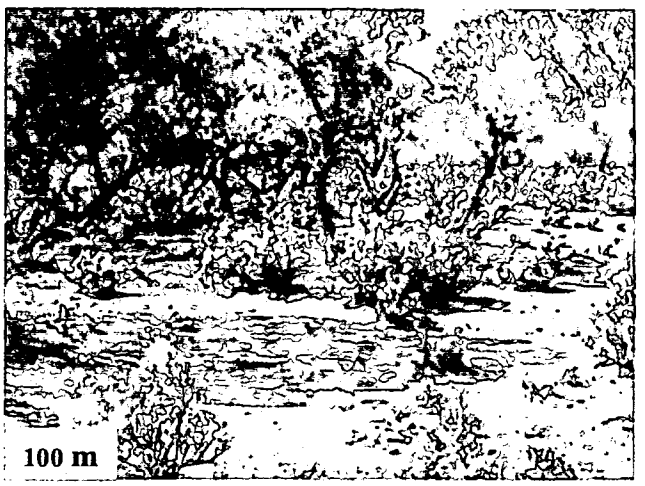
Appendix A-1. Datasheet of field cover data collection using the line-intercept method after Belnap *et al.* (2001)

Paddock:	Site Name:	Date: Start : Finished:	Latitude: Longitude:
Treatment:	Transect #:	Reader:	Recorder:

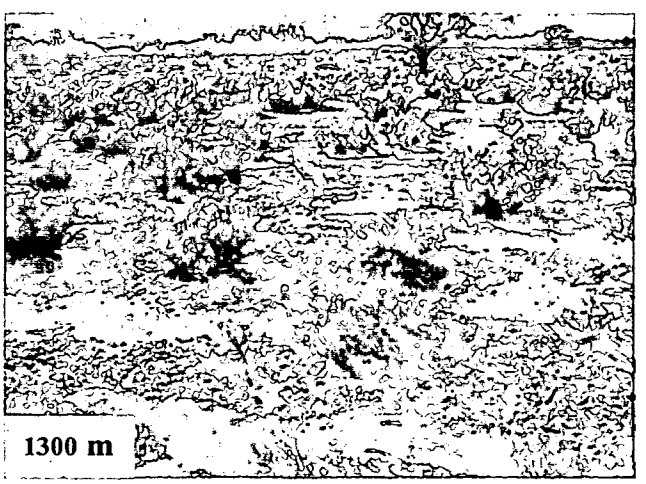
Cover Type	From (cm mark)	To (cm mark)	Under (Cover Type)	Cover Type	From (cm mark)	To (cm mark)	Under (Cover Type)

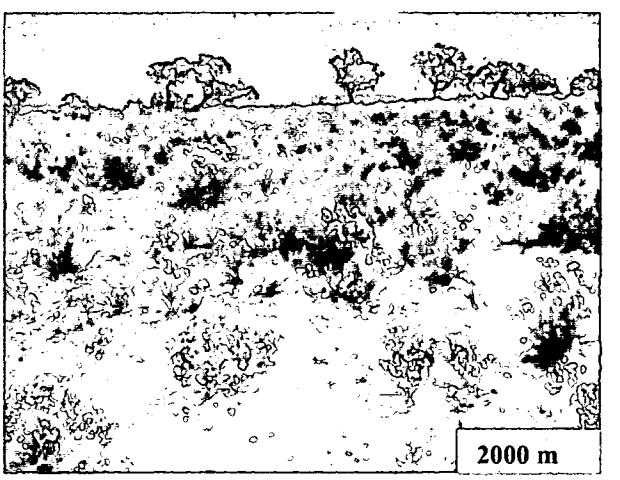
Photographs of 30 Sampling Sites

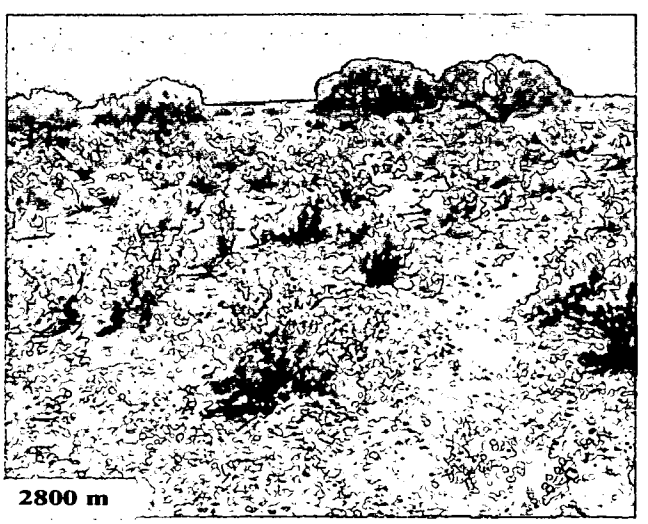
Appendix A-2. Balah paddock, different distances from the watering point (sites of collected data)

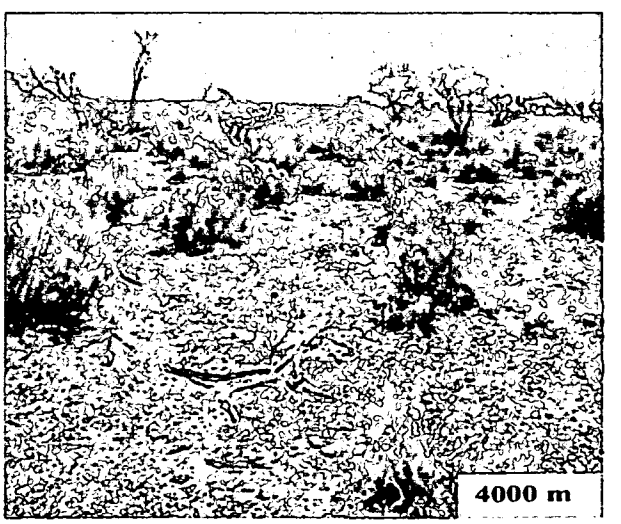




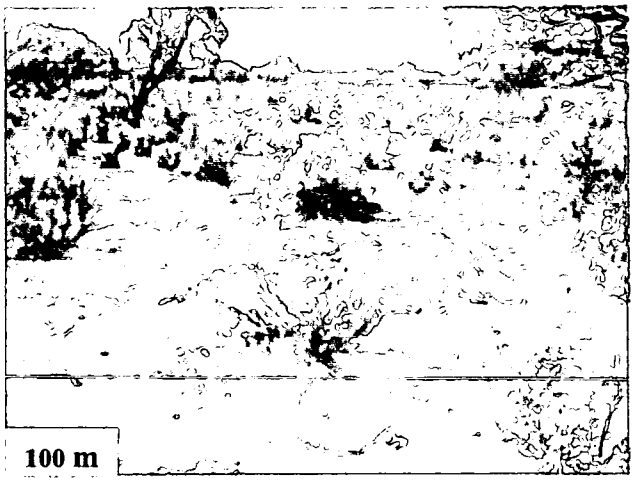


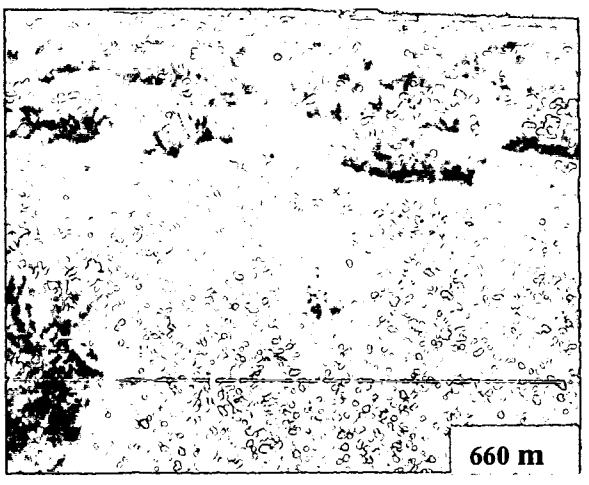


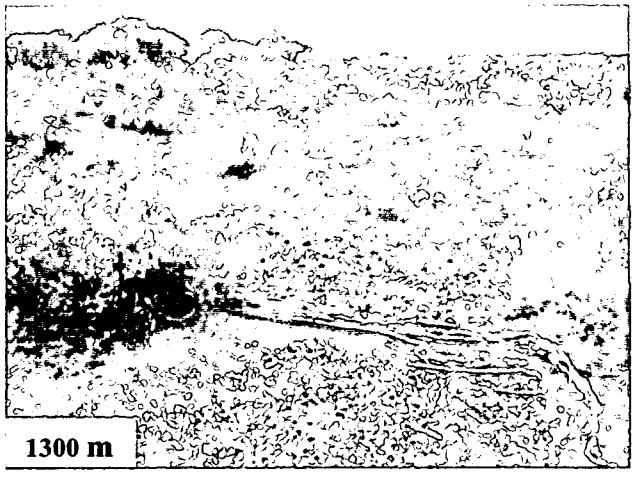


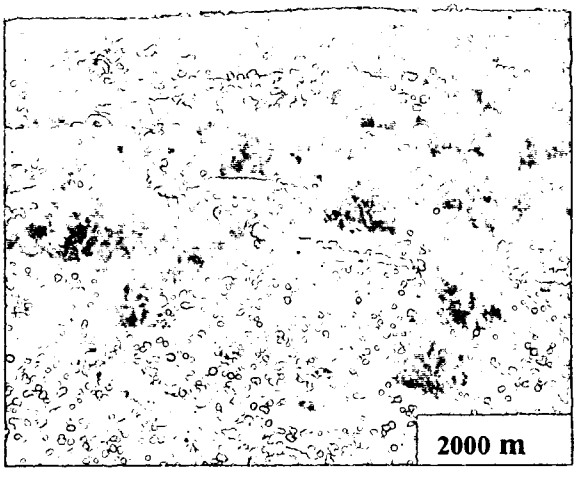


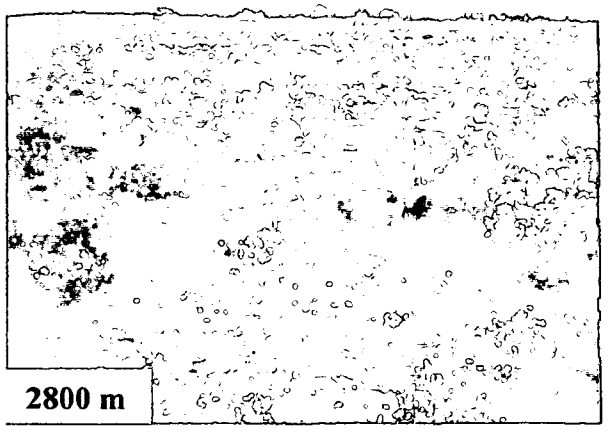
Appendix A-3. Billabong paddock, different distances from the watering point (sites of collected data)

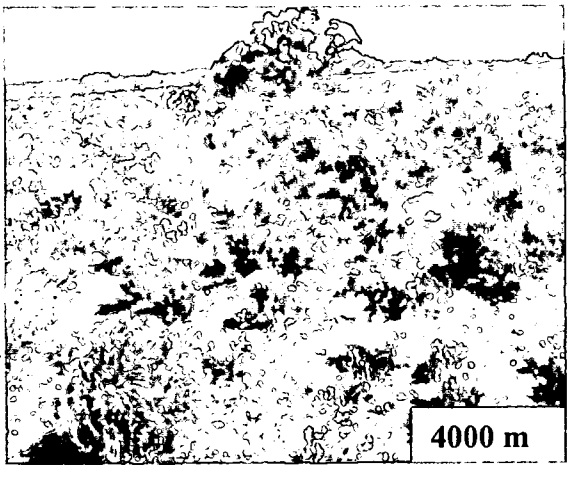




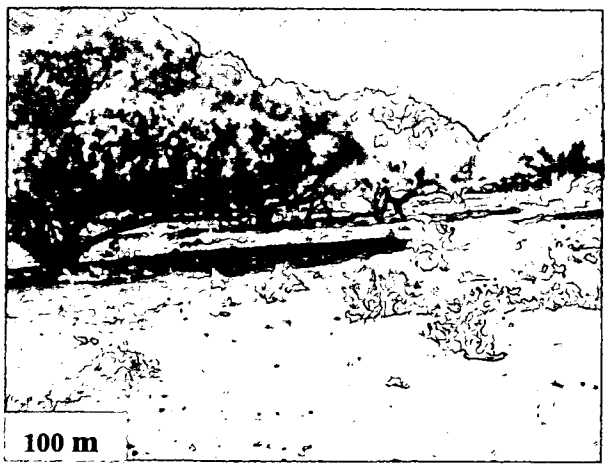


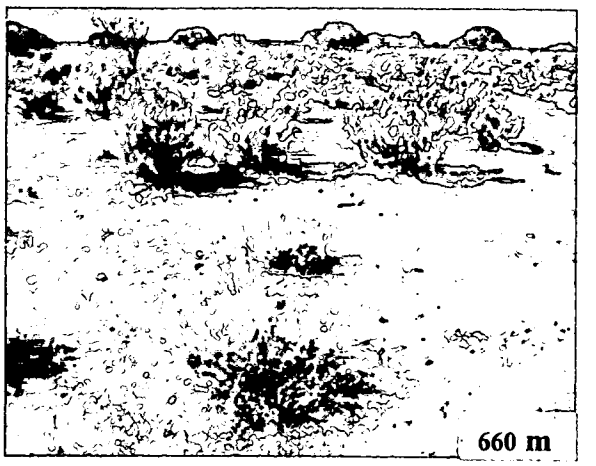


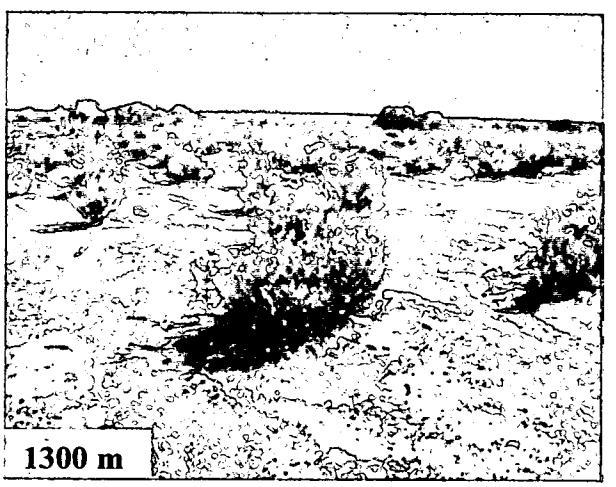


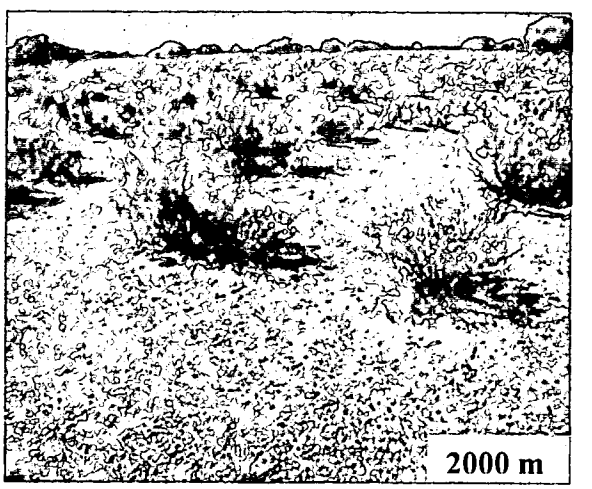


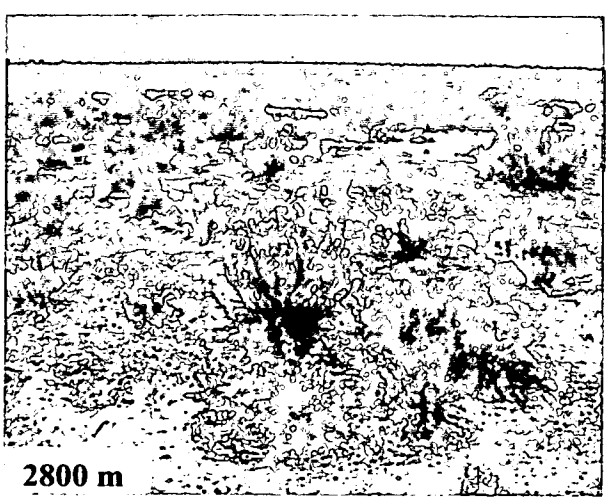
Appendix A-4. Corio paddock, different distances from the watering point (sites of collected data)

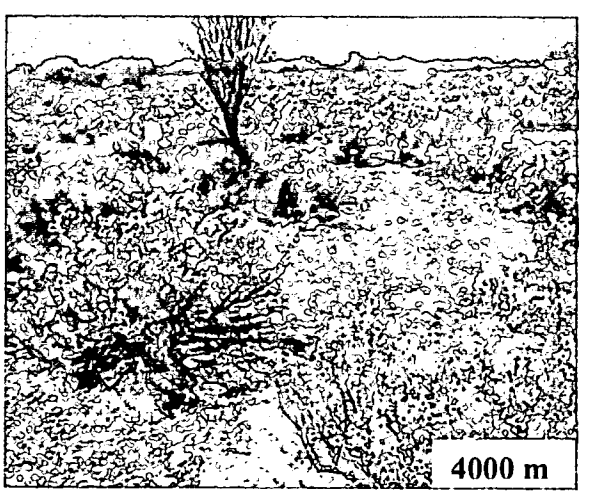




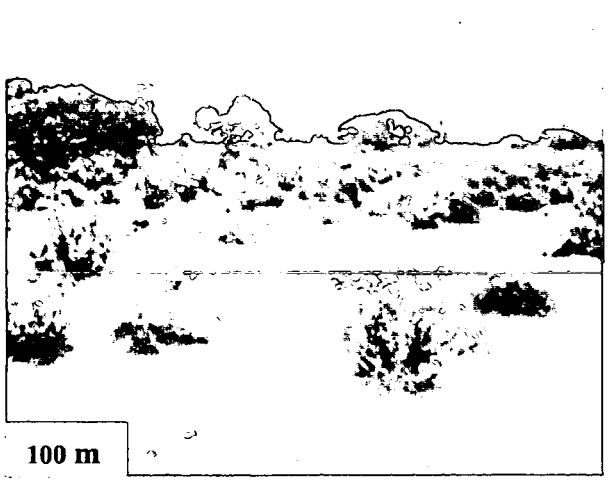


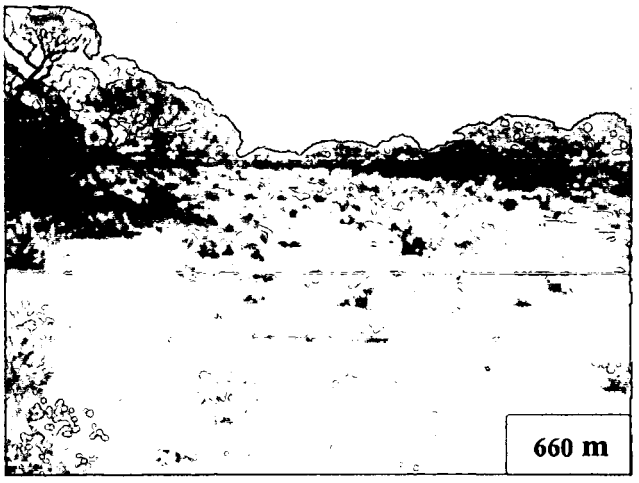


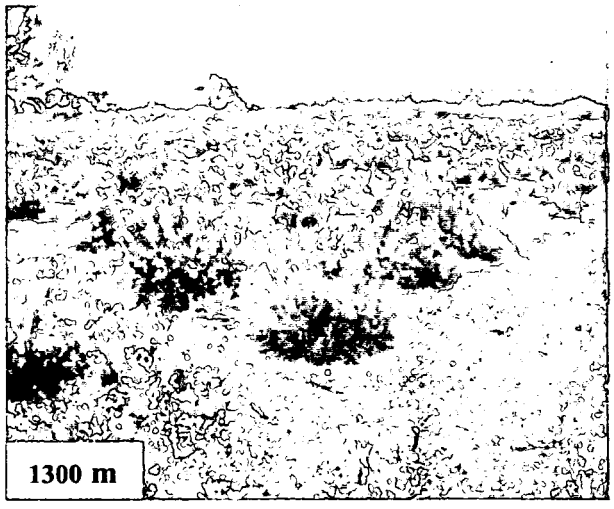


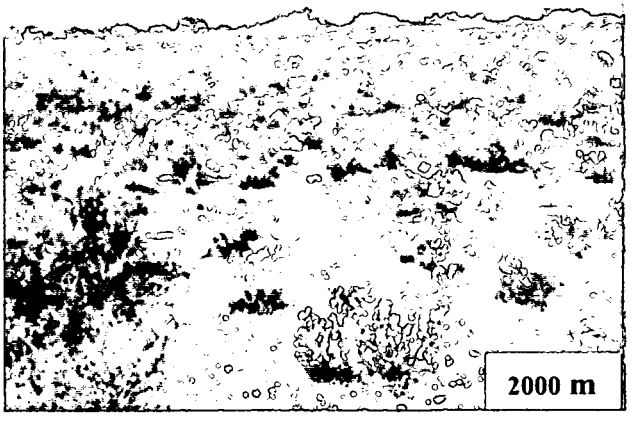


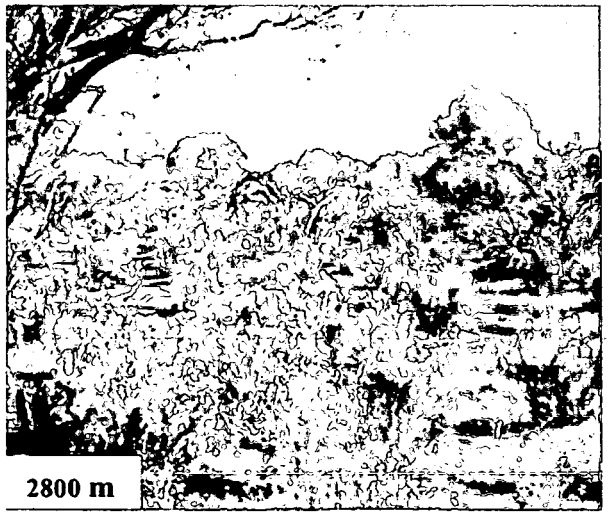
Appendix A-5. Purpunda paddock, different distances from the watering point (sites of collected data)





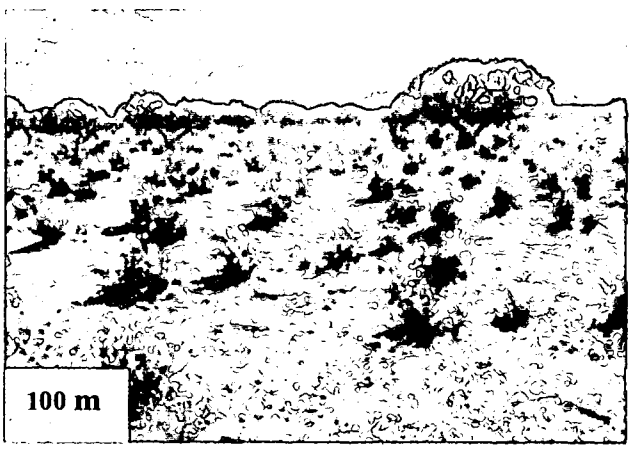


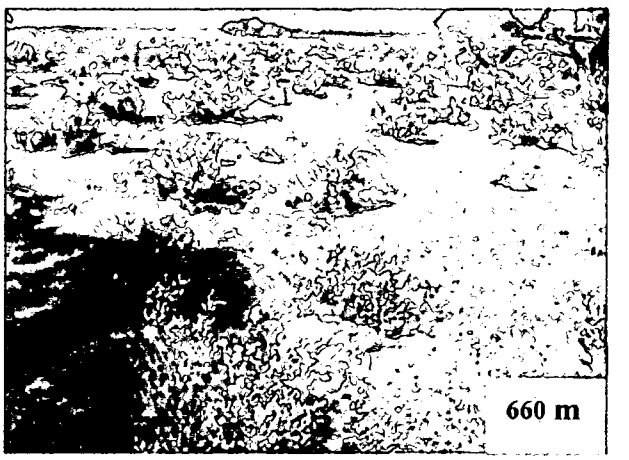


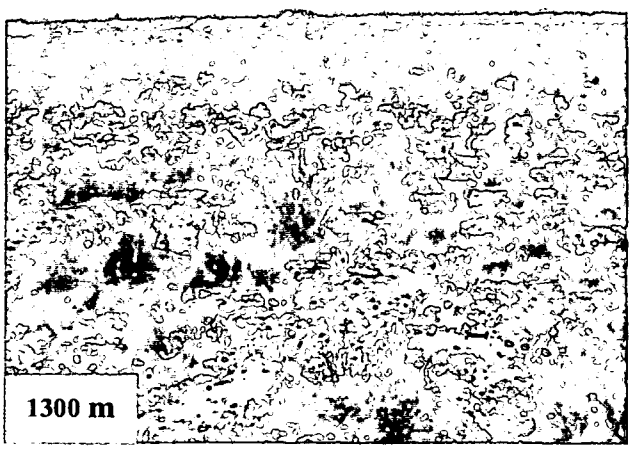


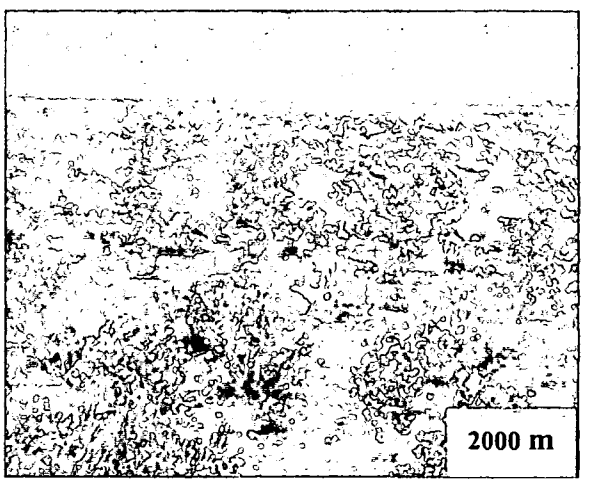


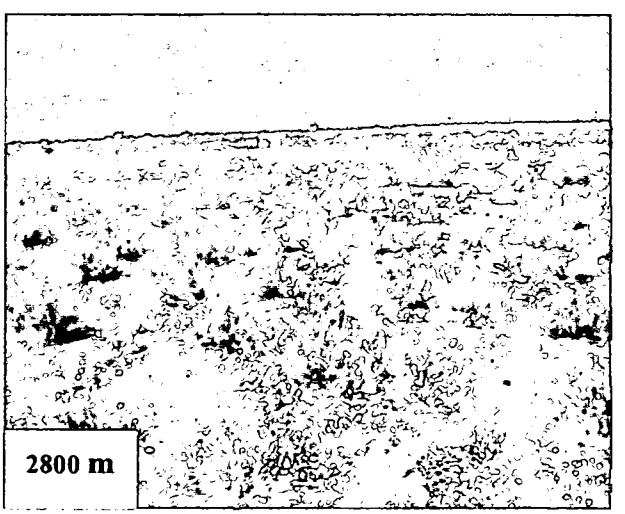
Appendix A-6. Railway paddock, different distances from the watering point (sites of collected data)

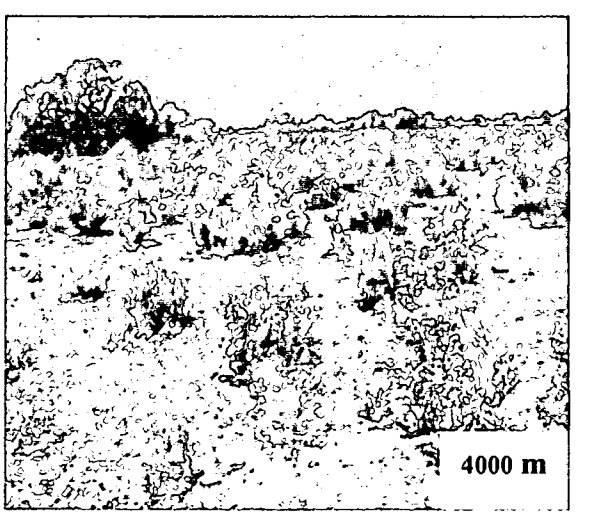




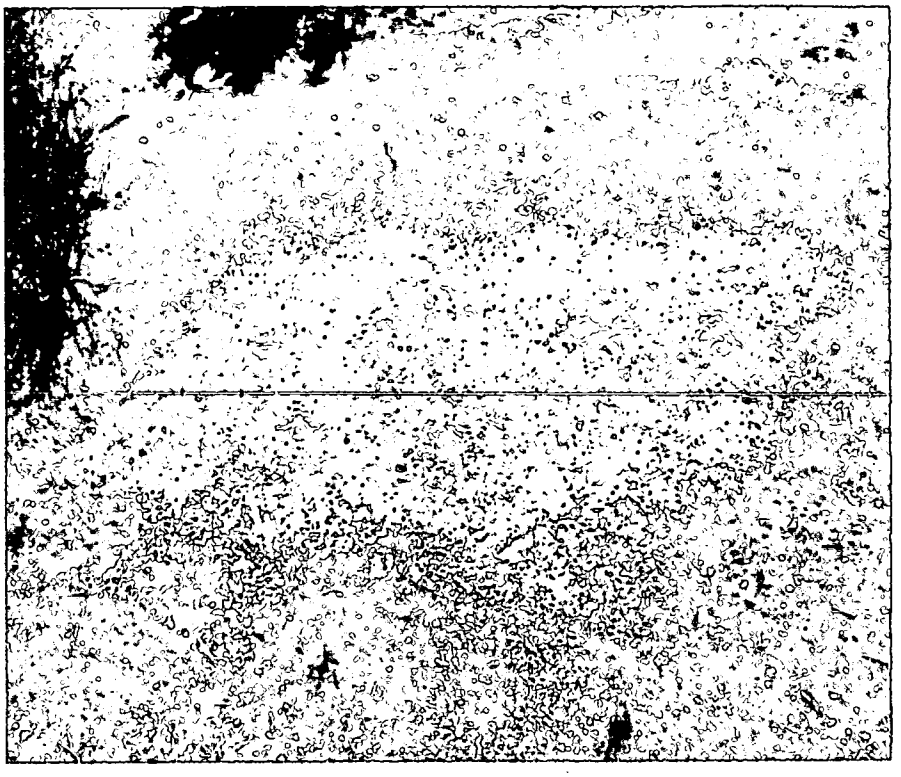








Appendix A-7. Soil patches at MFC

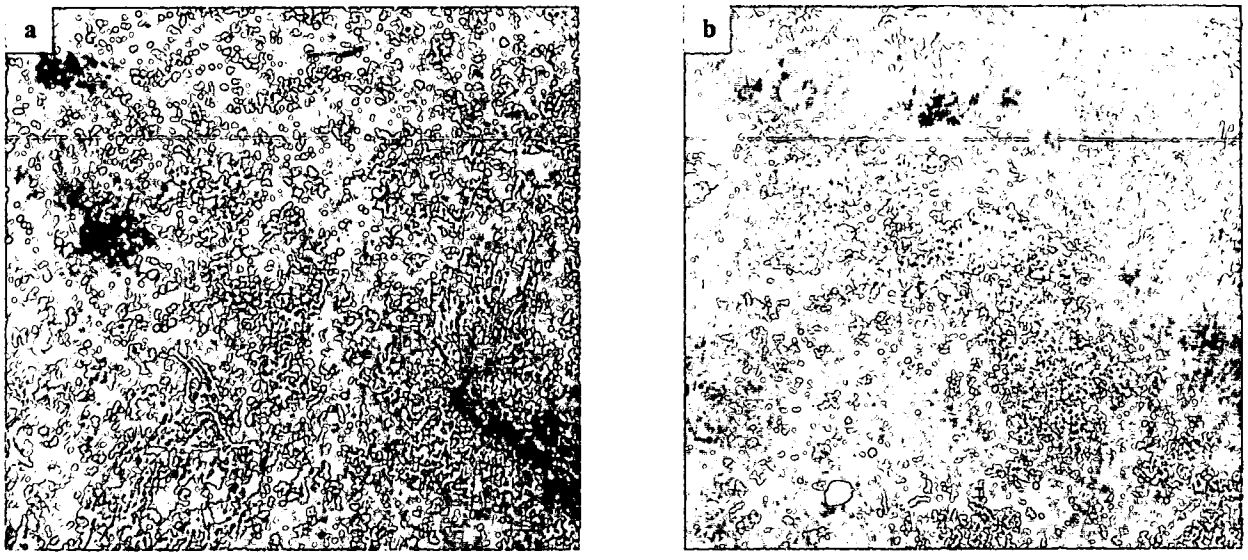


Appendix B-1. Cover of different BSC groups in different paddocks (the percentage is the proportion of the total BSC cover in each paddock / relative cover)

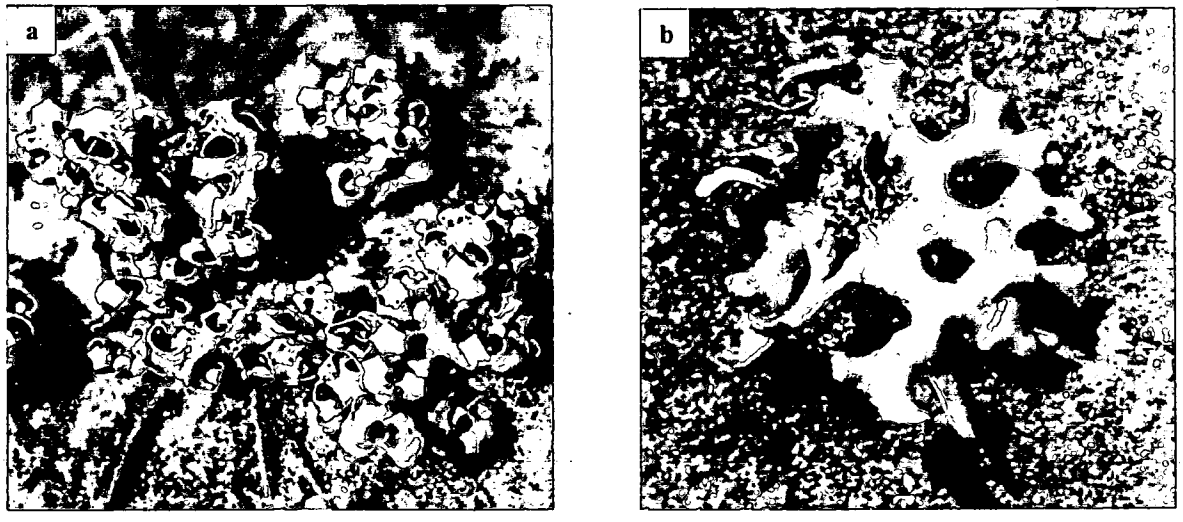
Paddocks	Balah %	Billabong %	Corio %	Purpunda %	Railway %	Mean %
Black Common Lichens	56.04	65.78	60.70	60.80	66.91	62.05
Scaly Lichens	13.29	9.24	18.57	11.52	8.90	12.30
Crusty Lichens	1.24	0.98	2.86	3.04	1.36	1.89
Leafy Lichens	6.61	0.83	1.42	4.73	0.60	2.84
Black Common Mosses	22.23	23.07	15.73	18.57	21.32	20.18
Tall Mosses	0.37	0.00	0.21	0.78	0.91	0.45
Others (stone-based +...)	0.22	0.10	0.51	0.56	0.00	0.28
Total	100.00	100.00	100.00	100.00	100.00	100.00

Example photographs: BSC sites, communities, dry and wet conditions and morphological / functional groups

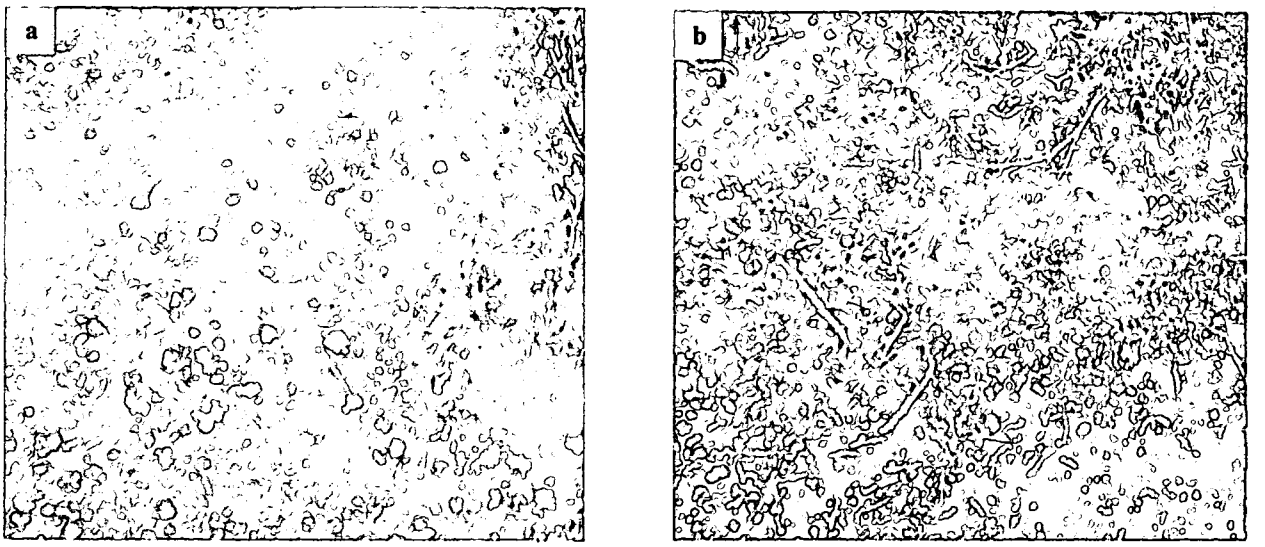
Appendix B-2. a) A typical example of the sites with more than 45% BSC cover, with the dominance of black BSC components; b) a unique example of Leafy Lichens community (outside of the Railway paddock)



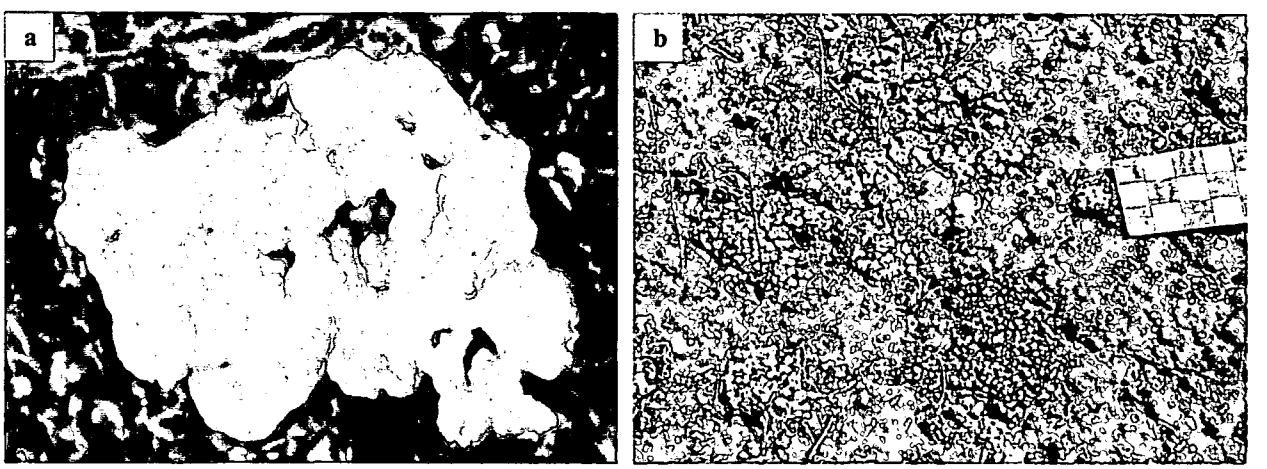
Appendix B-3. An example of Leafy Lichens in dry (a) and wet (b) conditions



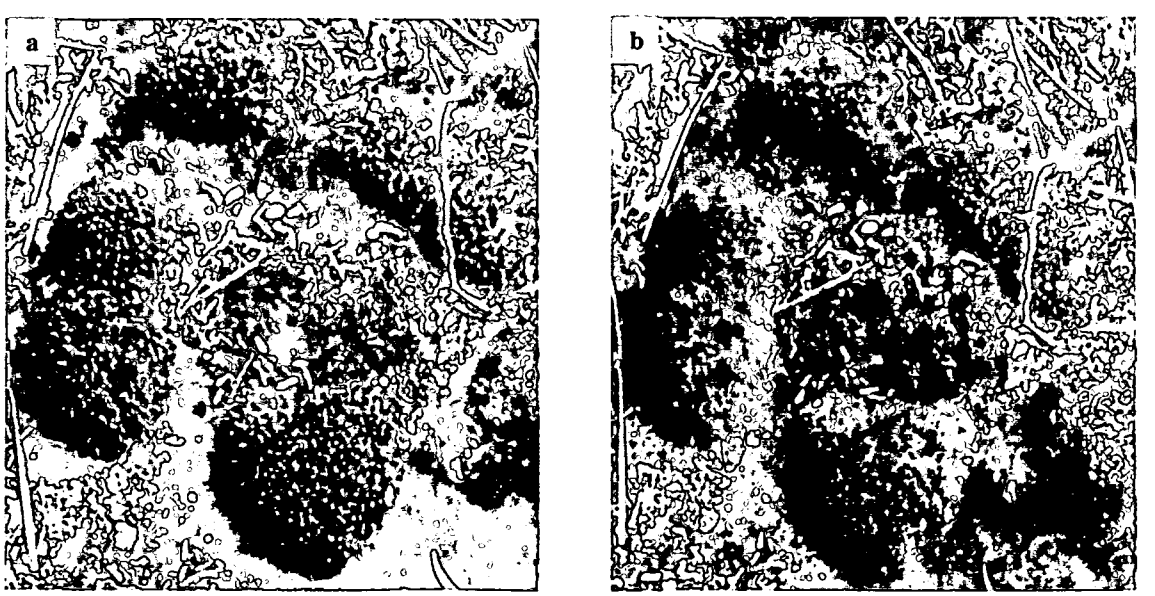
Appendix B-4. a and b) Examples of BSC cover in wet conditions with a dominance of moss components. Photos were taken after a 2 mm rainfall pulse at 100 m from water in Purpunda paddock. Unique communities which are not common in other paddocks at 100 m from water.



Appendix B-5. a) A typical example of Crusty Lichens; b) a typical example of BSC communities at MFC, with Black Common Lichens, mosses, and Scaly Lichens



Appendix B-6. An Example of tall mosses in dry (a) and wet (b) conditions



Appendix C-1. Land cover components in different paddocks and sites

Transects (Distance from water)	Bare Ground	Litter	Vascular Plants % Cover									BSC % Cover	
			Bluebush (*Maireana sedifolia*)	Blackbush (*M. pyramidate*)	*Atriplex vesicaria*	Other woody bushes	Trees	Grasses	Forbs	Total Annuals		Lichens	Mosses
										Grasses	Forbs		
Balah Paddock													
Tr100m	58.80	13.20	3.85	0.25	0.00	0.40	15.5	0.00	0.00	0.90	7.00	0.10	0.05
Tr660m	64.17	15.30	4.04	1.68	0.00	3.77	0.00	0.03	0.15	0.90	0.20	8.70	1.06
Tr1300m	57.69	10.80	4.05	1.80	1.42	0.50	0.00	0.00	0.00	0.00	0.00	22.30	1.15
Tr2000m	45.24	12.02	9.38	2.63	2.84	3.25	4.50	0.00	0.36	0.00	0.00	14.97	4.81
Tr2800m	48.08	4.40	4.28	1.90	2.47	0.00	0.00	0.00	0.77	0.00	0.90	31.30	5.75
Tr4000m	26.07	10.02	10.48	1.66	2.02	0.00	0.80	0.00	1.00	0.00	1.80	28.60	17.50
Billabong Paddock													
Tr100m	61.11	9.08	12.30	0.00	0.00	0.00	0.00	0.00	0.15	4.70	10.20	0.93	1.58
Tr660m	60.46	4.53	11.05	1.27	2.58	0.00	0.00	0.00	0.10	0.00	0.95	16.89	2.17
Tr1300m	59.42	5.31	12.40	0.00	0.80	0.00	0.00	0.02	1.39	0.03	0.00	13.92	6.63
Tr2000m	58.16	7.12	1.45	3.38	2.02	0.84	0.00	0.00	0.92	0.00	0.00	18.90	7.21
Tr2800m	37.97	11.20	0.44	4.30	11.20	0.00	0.00	0.02	2.79	0.00	0.00	25.38	6.75
Tr4000m	34.06	9.01	0.00	7.30	8.12	0.20	0.00	0.00	2.37	0.04	0.06	29.71	9.16
Corio Paddock													
Tr100m	75.66	3.12	1.66	0.00	0.00	0.06	18.00	0.00	0.06	0.57	0.91	0.02	0.00
Tr660m	54.23	4.86	11.87	0.00	4.07	0.27	0.00	0.00	0.00	0.00	0.17	20.89	3.64
Tr1300m	68.49	1.76	13.81	0.00	0.56	0.04	0.00	0.00	0.04	0.30	2.04	12.60	0.40
Tr2000m	47.40	8.14	5.88	0.00	0.70	0.00	0.00	0.00	0.08	0.00	0.00	29.32	8.50
Tr2800m	48.01	4.79	9.07	0.00	1.56	0.12	0.00	0.00	0.12	0.02	0.03	33.25	3.15
Tr4000m	46.43	4.79	8.02	0.00	0.60	4.35	1.20	0.00	0.10	0.04	0.03	30.60	3.84
Purpunda Paddock													
Tr100m	46.49	12.60	7.78	3.85	0.00	1.25	7.10	0.00	0.00	0.01	15.93	3.80	1.24
Tr660m	49.81	9.04	5.41	3.44	2.55	0.40	11.56	0.00	0.00	0.52	0.63	15.49	1.27
Tr1300m	29.27	7.71	14.33	1.59	0.13	0.00	4.45	0.00	0.00	0.08	12.39	24.40	3.33
Tr2000m	33.60	8.11	4.28	3.54	5.26	0.00	0.00	0.00	0.09	0.00	0.00	31.71	13.45
Tr2800m	27.93	9.37	14.26	0.68	0.52	0.62	16.16	0.00	0.17	0.01	0.62	22.38	7.90
Tr4000m	34.11	13.57	11.77	4.12	2.54	0.50	9.60	0.00	0.10	0.18	0.42	22.23	1.73
Railway Paddock													
Tr100m	66.25	8.29	7.20	0.06	0.53	0.00	3.13	0.00	0.00	5.12	8.36	0.90	0.20
Tr660m	63.80	11.60	11.30	1.60	3.50	0.20	0.00	0.00	0.00	1.60	2.30	2.90	1.23
Tr1300m	46.40	10.40	0.00	0.45	13.15	1.23	0.00	0.00	0.02	0.62	1.05	21.83	4.85
Tr2000m	44.85	11.00	2.82	4.02	7.04	0.00	0.00	0.00	0.02	0.00	0.08	22.73	7.44
Tr2800m	46.08	12.04	1.85	8.38	5.63	0.00	0.00	0.00	0.00	0.81	0.85	18.36	5.99
Tr4000m	39.85	15.86	3.90	0.14	2.80	0.08	1.20	0.00	0.10	0.27	0.53	27.90	7.34

Appendix C-2. Statistical analysis details for total BSC cover for exponential fitted curve

Extended analysis of variance to incorporate linear model

	d.f.	Sum of Sq	Mean Sq	F Value	P(F)
Paddock	4	73.215	18.304	0.32711	0.8564441
Distance	5	4173.575	834.715	14.91755	0.0000037
Linear	1	3431.953	3431.953	61.33392	0.0000002
Deviation	4	741.622	185.405	3.31346	0.0308748
Residuals	20	1119.105	55.955		

model Means
35 fitcurve [CURVE=exponential] Distance

Nonlinear regression analysis

Response variate: Means
Explanatory: Distance
Fitted Curve: A + B*(R**X)
Constraints: R < 1

Summary of analysis

Source	d.f.	Sum of Sq	Mean Sq	F Value
Regression	2	826.144	413.072	144.58
Residual	3	8.571	2.857	
Total	5	834.715	166.943	

Percentage variance accounted for 98.3
Standard error of observations is estimated to be 1.69.

Estimates of parameters

Parameter	Estimate	Standard Error
R	0.999182	0.000143
B	-38.31	2.33
A	36.99	2.11

Extended analysis of variance to incorporate exponential curve

	d.f.	Sum of Sq	Mean Sq	F Value	P (F)
Paddock	4	73.215	18.304	0.32711	0.8564441
Distance	5	4173.575	834.715	14.91755	0.0000037
Exponentiel	2	828.144	413.072	7.382218	0.00397144
Deviation	3	8.571	8.571	0.051059	0.984310929
Residuals	20	1119.105	55.955		

Appendix C-3. Statistical analysis details for total lichen cover for exponential fitted curve

Extended analysis of variance to incorporate linear model

	d.f.	Sum of Sq	Mean Sq	F Value	P(F)
Paddock	4	105.311	26.328	0.84277	0.5144368
Distance	5	2493.667	498.733	15.96484	0.0000022
Linear	1	2002.053	2002.053	64.08724	0.0000001
Deviation	4	491.614	122.904	3.93424	0.0162856
Residuals	20	624.790	31.239		

3 model Means
4 fitcurve [CURVE=exponential] Distance

Nonlinear regression analysis

Response variate: Means
Explanatory: Distance
Fitted Curve: A + B*(R**X)
Constraints: R < 1

Summary of analysis

Source	d.f.	Sum of Sq	Mean Sq	F Value
Regression	2	497.9941	248.9970	1010.48
Residual	3	0.7392	0.2464	
Total	5	498.7333	99.7467	

Percentage variance accounted for 99.8
Standard error of observations is estimated to be 0.496.

Estimates of parameters

Parameter	Estimate	Standard Error
R	0.9990602	0.0000587
B	-29.474	0.660
A	28.181	0.528

Extended analysis of variance to incorporate exponential curve

	d.f.	Sum of Sq	Mean Sq	F Value	P(F)
Paddock	4	105.311	26.328	0.84277	0.5144368
Distance	5	2493.667	498.733	15.96484	0.0000022
Exponential	2	497.9941	248.9971	7.970711	0.00284674
Deviation	3	0.7392	0.2464	0.007888	0.999004279
Residuals	20	624.79	31.239		

Appendix C-4. Statistical analysis (variances) details for total moss cover

	Variances	Std. Error	Z. Ratio
100	0.00000014746	NA	NA
660	1.93540000000	1.3685345	1.414213
1300	4.38457000000	3.1003596	1.414214
2000	8.52877000000	6.0307514	1.414214
2800	1.72223000000	1.2178008	1.414213
4000	40.3682000000	28.4182381	1.420503

Appendix C-5. Statistical details of Wald tests for fixed effects of total moss cover

Terms added sequentially; adjusted for those above				
	d.f.	Sum of Sq	Wald statistic	P (Chisq)
(Intercept)	1	3.4405	3.4405	0.0636162
Linear	1	126.1742	126.1742	0.0000000
Deviation	4	8.4411	8.4411	0.07669282
Residual		1.0000		

Appendix C-6. Statistical analysis for total black common lichen cover for exponential fitted curve

Extended analysis of variance to incorporate linear model

> summary (BC.lichen.aov, split = list(Distance = list(L = 1, Dev = 2:5)))

	d.f.	Sum of Sq	Mean Sq	F Value	P(F)
Paddock	4	24.779	6.195	0.23066	0.9178959
Distance	5	1529.736	305.947	11.39157	0.0000266
Linear	1	1103.296	1103.296	41.07990	0.0000030
Deviation	4	426.440	106.610	3.96949	0.0157205
Residuals	20	537.146	26.857		

Model means

35 fitcurve [CURVE=exponential] Distance

Nonlinear regression analysis

Response variate: Means

Explanatory: Distance

Fitted Curve: A + B*(R**X)

Constraints: R < 1

Summary of analysis

Source	d.f.	Sum of Sq	Mean Sq	F Value
Regression	2	301.194	150.597	95.06
Residual	3	4.753	1.584	
Total	5	305.947	61.189	

Percentage variance accounted for 97.4

Standard error of observations is estimated to be 1.26.

Estimates of parameters

Parameter	Estimate	Std. Error
R	0.998939	0.000208
B	-22.87	1.66
A	21.23	1.18

Extended analysis of variance to incorporate exponential curve

	d.f.	Sum of Sq	Mean Sq	F Value	P(F)
Paddock	4	24.779	6.195	0.23066	0.9178959
Distance	5	1529.736	305.947	11.39157	0.0000266
Exponential	2	1505.97	752.985	28.03682	0.00000158
Deviation	3	13.067	4.355667	0.16218	0.920543515
Residuals	20	537.146	26.857		

Appendix C-7. Statistical analysis (variances) details for scaly lichen cover

	Variances	Std. Error	Z. Ratio
100	0.011720397	0.03000165	0.3906584
660	15.825047193	11.18873055	1.4143738
1300	6.386096116	4.52106935	1.4125189
2000	1.167272596	0.83018675	1.4060362
2800	15.559757655	11.00086094	1.4144127
4000	0.272304478	0.20026405	1.3597272

Appendix C-8. Statistical details of Wald tests for fixed effects of scaly lichen cover

Terms added sequentially; adjusted for those above				
	d.f.	Sum of Sq	Wald Statistic	P(Chisq)
(Intercept)	1	44.2390	44.2390	0.00000000
Linear	1	579.0149	579.0149	0.00000000
Deviation	4	11.0304	11.0304	0.0262244
Residual		1.0000		

Appendix C-9. Statistical analysis (variances) details for total crusty lichen cover

	Variances	Std. Error	Z. Ratio
100	0.0001799995	0.0001269769	1.417577
660	0.1038300000	0.0734188971	1.414214
1300	0.5247781108	0.3700198917	1.418243
2000	0.1987300000	0.1405233214	1.414214
2800	0.6910175674	0.4822895446	1.432786
4000	0.2935300000	0.2075533173	1.414239

Appendix C-10. Statistical details of Wald tests for fixed effects of crusty lichen cover

Terms added sequentially; adjusted for those above				
	d.f.	Sum of Sq	Wald Statistic	P(Chisq)
(Intercept)	1	1.76416	1.76416	0.1841060
Linear	1	30.13010	30.13010	0.0000000
Deviation	4	2.71698	2.71698	0.6062475
Residual		1.00000		

Appendix C-11. Statistical analysis (variances) details for leafy/shrubby lichen cover

	Variances	Std. Error	Z.Ratio
100	0.0	NA	NA
660	0.26263000	0.1857075	1.414214
1300	0.10203000	0.0721461	1.414214
2000	4.97084401	3.4943770	1.422527
2800	0.25267000	0.1786647	1.414214
4000	0.56347000	0.3984335	1.414214

Appendix C-12. Statistical details of Wald tests for fixed effects of total Leafy Lichen cover

Terms added sequentially; adjusted for those above				
	d.f.	Sum of Sq	Wald statistic	P(Chisq)
(Intercept)	1	5.897361	5.897361	0.0151636
Linear	1	8.698317	8.698317	0.0031850
Deviation	4	1.858680	1.858680	0.7617309
Residual		1.000000		

Appendix C-13. Statistical analysis (variances) details for black common moss cover

	Variances	Std. Error	Z.Ratio
100	0.42678	0.3017790	1.414214
660	1.01897	0.7205206	1.414214
1300	6.30960	4.4615609	1.414214
2000	10.44467	7.3854970	1.414214
2800	3.11950	2.2058196	1.414214
4000	38.17335	26.8845144	1.419901

Appendix C-14. Statistical details of Wald tests for fixed effects of total black common moss cover

Terms added sequentially; adjusted for those above				
	d.f.	Sum of Sq	Wald Statistic	P (Chisq)
(Intercept)	1	49.81411	49.81411	0.0000000
Linear	1	64.12909	64.12909	0.0000000
Deviation	4	6.76467	6.76467	0.1488596
Residual		1.00000		

Appendix C-15. Statistical analysis (variances) details for tall moss cover

	Variances	Std. Error	Z.Ratio
100	0.09799195	0.068356485	1.433543
660	0.00612000	0.004327494	1.414214
1300	0.04232000	0.029923990	1.414250
2000	0.02330000	0.016475588	1.414214
2800	0.05492000	0.038821600	1.414676
4000	0.01952000	0.013802724	1.414214

Appendix C-16. Statistical details of Wald tests for fixed effects of tall moss cover

Terms added sequentially; adjusted for those above				
	d.f.	Sum of Sq	Wald statistic	P(Chisq)
(Intercept)	1	7.269430	7.269430	0.0070138
Linear	1	0.276401	0.276401	0.5990698
Deviation	4	1.320894	1.320894	0.8578207
Residual		1.000000		

Appendix D-1. Datasheet for phenological observations

Location: Paddock .....Transect.....GPS way point.....													
Phenological Stages	Date												
Visit Date													
Annual Plants	Start												
	Peak												
	Drying Date												
Perennial Plants	Start												
	Peak												
	Drying Date												
Biological Soil Crusts	Start												
	Peak												
	Drying Date												

Appendix E-1. Rainfall data for the four stations (MFC, Iron Knob, Roopena and Whyalla), missing years and estimated years data are in bold format. Base data for missing data estimation for all stations were MFC dataset. The employed simple regression models for prediction of missed data in each station are presented at the end of the table. A total of 80 years' data were used as the first based line in the data analysis and highlighted years are used as the second baseline for 26 years.

Year	MFC	Mean	Whyalla	Mean	Roopena	Mean	Iron Knob	Mean
1925	149				118.4		110.9	
1926	217				215.3		201.9	
1927	105				77.9		104.5	
1928	173				140.7		141.4	
1929	133				113.5		136.1	
1930	216				164.6		195.3	
1931	186				179.5		185.5	
1932	196				257.7		239.9	
1933	192				174.6		153.3	
1934	169				160.9		148.7	
1935	192				195.8		176.6	
1936	131				193.3		160	
1937	238				292.5		209.1	
1938	228				258.3		225.2	
1939	182				180.4		202.1	
1940	91				92.1		97.1	
1941	215				209.2		200.9	
1942	266				254.4		257.2	
1943	98				107.9		**104.8**	
1944	165				191.4		188.7	
1945	168				195.2		168.8	
1946	391				319.2		355.9	
1947	202				201.7		257.7	
1948	101		238.9		102		111	
1949	197				196.1		197.9	
1950	204				192.4		235.7	
1951	192				189.4		149.1	
1952	251				233.3		300.9	
1953	185				184.9		214.5	
1954	255				256		271.5	
1955	201				292.5		232.2	
1956	210				**207.8**		217.8	
1957	100				92.1		82.9	
1958	195				241		218.3	
1959	159				126.1		120.4	
1960	232				216.9		296.2	
1961	204				187.5		229.7	
1962	168				170.4		187.1	
1963	246				273.7		319.6	
1964	127				153.1		167.6	
1965	135				140.7		137.2	

Table E-1. Continued

1966	313				252.8		279.1	
1967	163	218.53		277.69	147.7	213.23	152.2	218.41
1968	301				365		347.8	
1969	236				254.2		248.1	
1970	149				106.7		136.6	
1971	212				234.4		215.9	
1972	198.6				151.4		181.4	
1973	511.1				505.1		477.8	
1974	507.8				536.7		545	
1975	215.8				213.8		249.4	
1976	199.58				198.3		183.8	
1977	126.6				144.3		148	
1978	223.4				252.1		246	
1979	450.8		510.3		447.7		437	
1980	244.4		248.8		214.1		218	
1981	218		244.1		252.7		286	
1982	113.2		155.5		87.5		108	
1983	226.4		282.4		251.2		223	
1984	208.4		245.8		197.7		242	
1985	163.6		211.9		170.5		181	
1986	248.8		294.4		228.4		243	
1987	217.8		260.4		201.7		202	
1988	168.8		174.9		130.9		161.5	
1989	231.2		335.4		213.3		265	
1990	194.6		216.6		203		165.4	
1991	190		**226.5**		175.9		180.6	
1992	476.8		**527.7**		463.3		469.3	
1993	338.4		**382.4**		240.7		**336.6**	
1994	147.6		**182.0**		142.7		**152.6**	
1995	262.8		409.8		293.3		213	
1996	261.85		244.9		227.4		164	
1997	283.2		365.7		322.6		321.9	
1998	331.35		302.6		258.8		285	
1999	253.1		253.7		212		217.3	
2000	205.55		249.7		256.9		219.8	
2001	320.5		362.7		268.3		351.2	
2002	118		146.8		125.5		**124.1**	
2003	221.5		266.4		202.4		205.2	
2004	146.6	218.53	157.3	277.69	156.7	213.23	178.1	218.41

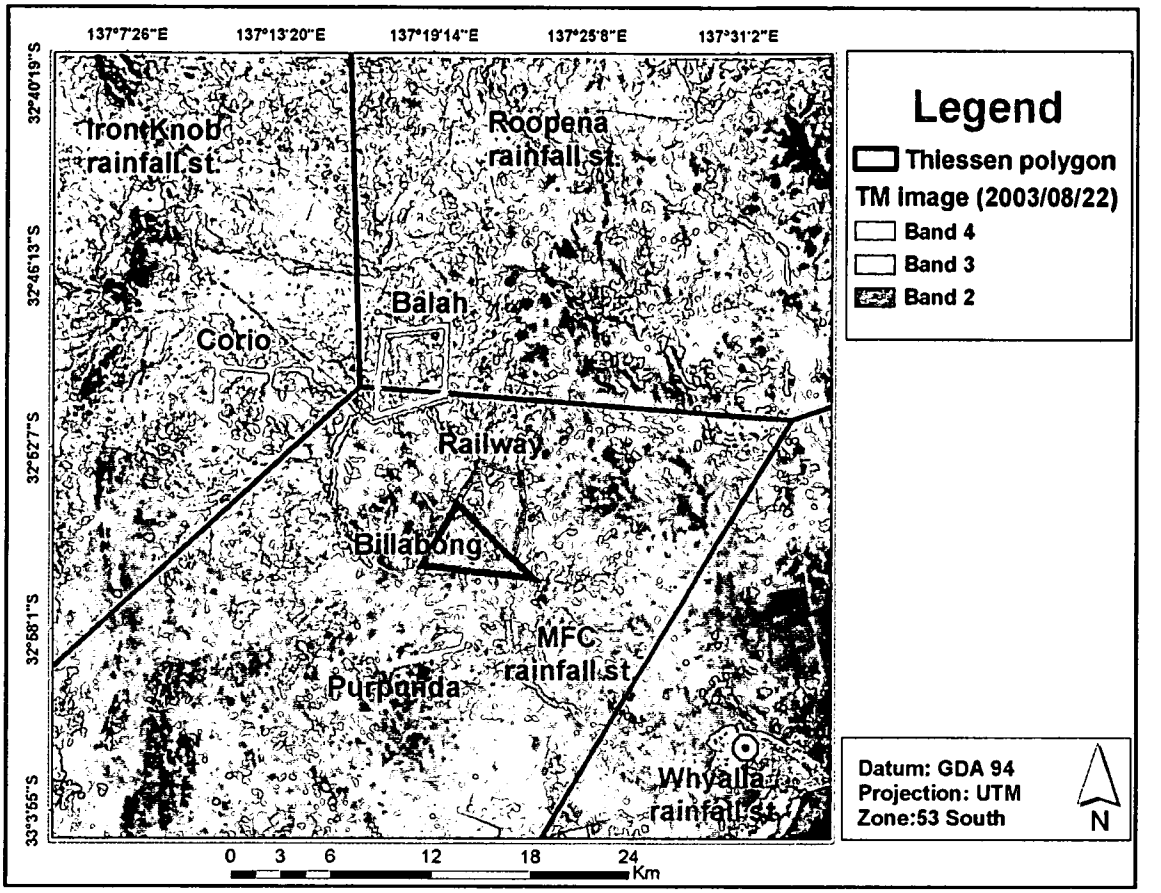
Regression equations for missed data estimation

$Y = 0.9419x + 9.9575$	for the Roopena station
$Y = 0.09643x + 10.304$	for the Iron Knob station
$Y = 1.0501x + 27.018$	for the Whyalla station

Appendix E-2. Fieldwork timetable and data collection

Fieldtrip	Date	Ground-based data collection	Spectra collection
1	2003/3/20 to 23	Pre-visit of study field	Ground control points collection
2	2003/6/19 to 22	Paddock defining/ data collection in Railway paddock for pilot study /BSC specimen collection	**Spectra collection** for pilot study from different objects
3	2003/9/19 to 23	Data collection for pilot study with different methods / BSC specimens collection	No Spectra / because of computer limitation
4	2003/11/19 to 21	Data collection for pilot study with different methods / BSC specimen collection	**Spectra collection**
5	2003/12/21 to 24	Ground-based data collection	**Spectra collection**
6	2004/1/20 to 26	Ground-based data collection	**Spectra collection**
7	2004/2/22 to 25	Ground-based data collection	**Spectra collection**
8	2004/5/20 to 22	Ground-based data collection	Spectrometer limitation
9	2004/6/20 to 23	Ground-based data collection	Spectrometer limitation
10	2004/7/28 to 8-5	Ground-based data collection	Spectrometer limitation
11	2004/8/25 to 30	Ground-based data collection	**Spectra collection**
12	2004/9/19 to 23	Ground-based data collection	Spectrometer limitation
13	2004/9/29 to 10-6	Ground-based data collection	**Spectra collection**
14	2004/11/26 to 29	Ground-based data collection	**Spectra collection** / Experiment for moisture stability
15	2004/12/18 to 24	Ground-based data collection	Planned moisture stability experiment for summer was cancelled because of spectrometer limitation
16	2005/1/15 to 24	Ground-based data collection	Planned moisture stability experiment for summer was cancelled because of spectrometer limitation
17	2005/3/23 to 29	Ground-based data collection / last data	**Spectra collection** / Experiment for moisture stability/ Spectra for radiometric calibration
18	2005/4/22 to 29	Phenology and stratification accuracy control	**Spectra collection** / Experiment for moisture stability / Spectra for radiometric calibration
19	2005/7/15 to 21	Phenology and stratification accuracy control	Planned moisture stability experiment for winter was cancelled because of spectrometer limitation

Appendix E-3. Position of weather stations in relation to the study paddocks and a Thiessen polygon for deriving influence area and compatibility of each paddock with weather stations



Appendix E-4. Four main seasons of South Australia adapted from Berndt *et al.* (1993) and Jones (2002), names in brackets are Aboriginal term for these seasons.

Seasons	Intervals
Spring (Riwuri)	August to October
Summer (Luwadang)	November to January
Autumn (Marangani)	February to April
Winter (Yutang)	May to July

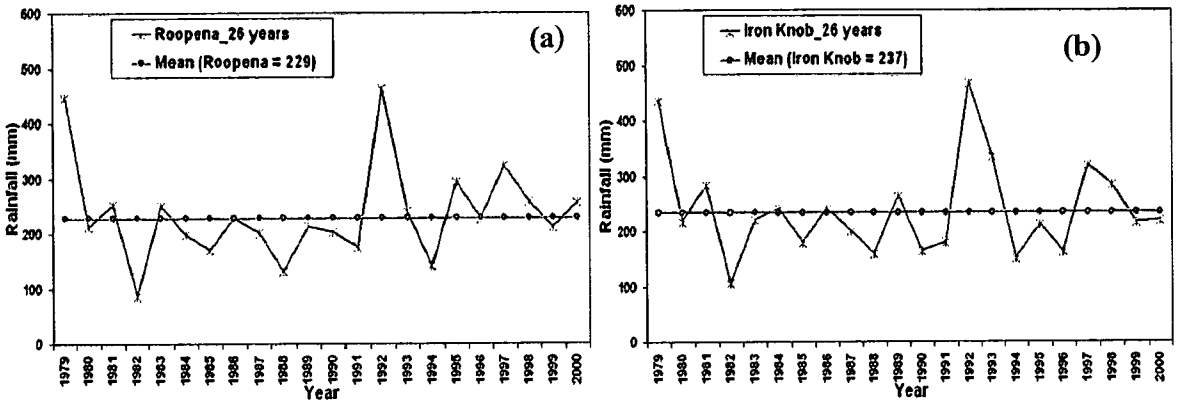
Appendix E-5. Season Timelines (intervals) of Australia adapted from Reid (1994), Reid & Beckett (1995) and Jameson (2001)

Season	"Timelines" (Intervals)
Pre-spring	16th July to 25th of August
True spring	26th August to 5th November
Early summer	6th November to 30th January
Late summer	1st February to 15th March
Autumn	16th of March to 31st of May
Winter	1st of June to 15 of July

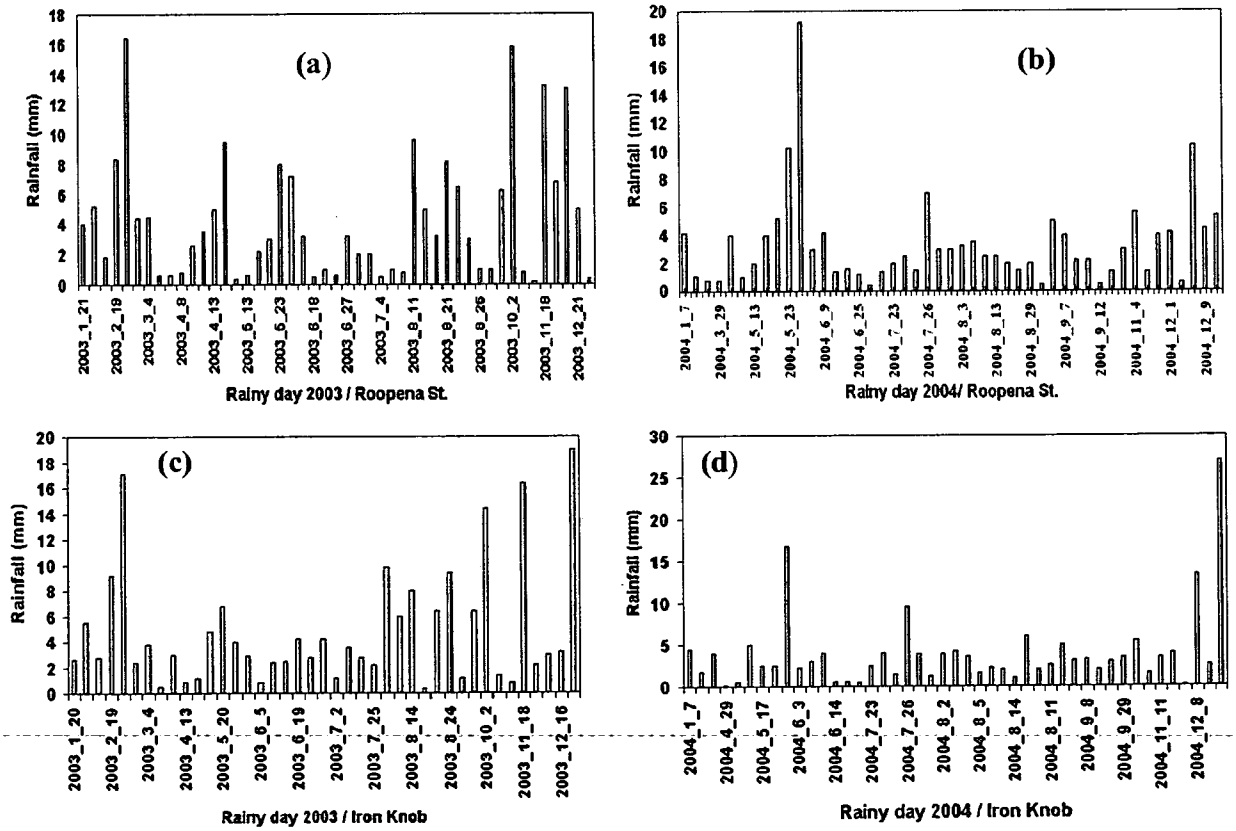
Appendix E-6. Phenological observation timetable

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
2003			X			X			X		X	X
2004	X	X			X	X	X	X	X	X	X	X
2005	X		X	X		X						

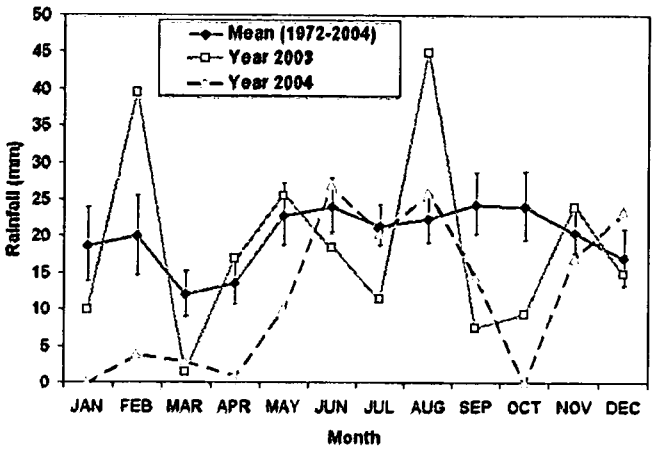
Appendix E-7. Medum-term rainfall for the study area over 26 years from 1979 to 2004: a) Roopena station and b) Iron Knob station



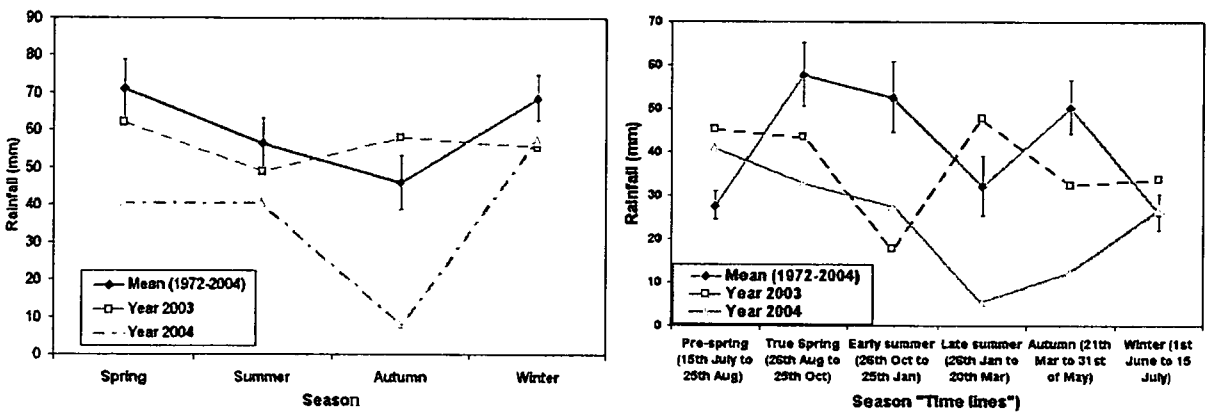
Appendix E-8. Rainy days during the study: a) Roopena year 2003; b) Roopena year 2004; c) Iron Knob year 2003, and d) Iron Knob 2004



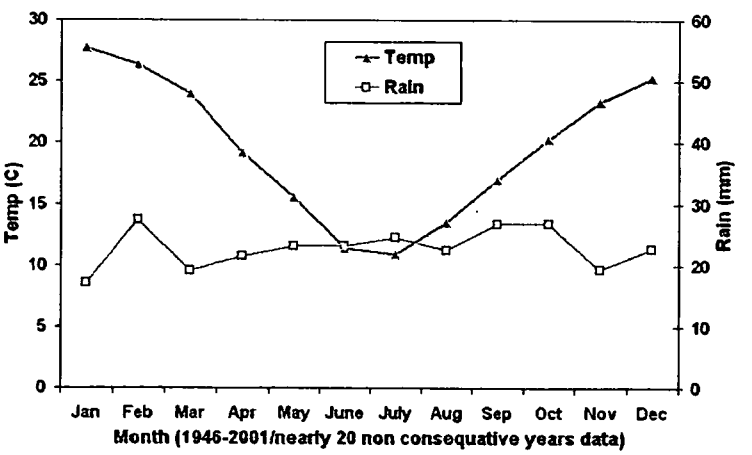
Appendix E-9. Monthly mean rainfall ± standard error (vertical bars) for 33 years (1972-2004) versus monthly rainfall in the study period (2003 and 2004)



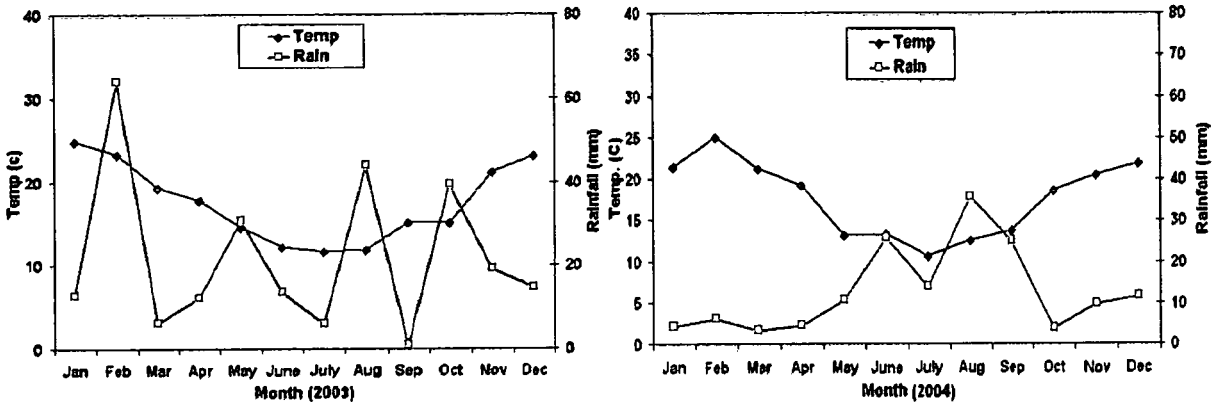
Appendix E-10. Cumulative mean rainfall ± standard error (vertical bars) for 33 years versus cumulative rainfall in the study period based on the a) European-based calendar and b) seasonal intervals "Timelines" of Australia at MFC



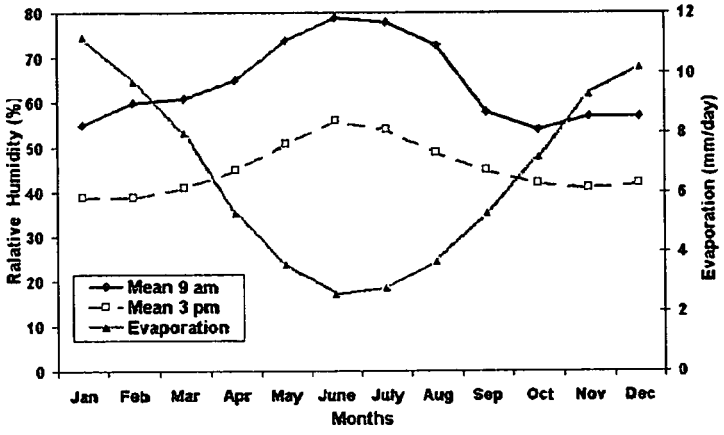
Appendix E-11. Joint effects of long- term mean monthly temperature and rainfall in the Whyalla station (data are presented in different scales)



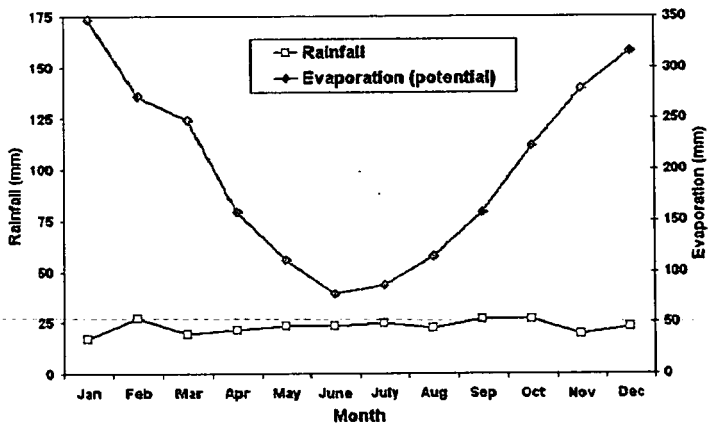
Appendix E-12. Climate diagram mean monthly temperature versus rainfall at the Whyalla station a) year 2003 and b) year 2004



Appendix E-13. Relative humidity for nearly 24 non-consecutive years and daily pan evaporation for nearly 7 non-consecutive years at the Whyalla station



Appendix E-14. Evaporation for nearly 7 non-consecutive years versus rainfall of 26 years at the Whyalla station



Appendix F-1. UniSpec manufacturer's technical specifications as of 1999 [comments in square brackets are the author's] (PPSystems, 1999)

Detector Type	VIS / NIR
Optical Sensing Range	300 nm to 1100 nm
Releigh Resolution	<10 nm
Bin Size	3.3 nm
Absolute Accuracy	<0.3 nm
Spectral Sampling/	UV Enhanced – increased sensitivity in the UV range [300-400nm] VIS Enhanced – increased sensitivity in the VIS range [400-550 nm] NIR Enhanced – increased sensitivity in the NIR range [875-1000 nm] [Sampling intervals given are averages. See Tips section for variations in spectral sampling interval with dispersion angle, especially in the SWIR]
A/D Converter	16 bit [dynamic range of 65, 536 A/D counts]
Data Interval	Not specified [Data interval, like the sampling interval, varies with dispersion angle]
Spectral Resolution	Not specified by manufactures but according to the wavelength column its 3.3 nm
Field of View	42° -45° (±2°) [calculated by Sedat Arkun 2000/ owner of the spectrometer](Arkun, 2004), and 3° (PPSystem 2004).
Repeatability	Within 0.1%
Scan Time	<0.5 second [(plus integration time) (5 to 15 scans are usually averaged in measuring the reflectance of a typical target for good S/N/ user defied number of scans)]
Integration Time	4 – 32,767 ms [longer times optional]
Power Source	Internal 6V 3.4 Ah lead acid battery ○ 35 hours with lamp off ○ 2 hours with continuous lamp use [Computer powered separately by internal battery consistent with model selected]
Light Source	Integral 7.0 Whalogen bulb
Digital Output	RS232 (19.2 Kboud)
Dimensions	19.5 cm long × 11.5 cm wide × 7.5 cm high
Operating Temp.	0-45°C [non-condensing]
Measurement type	Single beam bidirectional, requiring either a solar or an artificial external light source
Weight	Spectrometer head 2.3 kg + Laptop Computer [Operational use typically requires a tripod ~ 2 kg, unless the optional fiber optic cable can be used. The spectrometer carrying case supplied weighs 4.6 kg, but can be replaced by a light backpack.]

Appendix F-2. Weather data from Whyalla station during the periods of spectral data collection

Date	Temperature °C			Rainfall	Wind direction		Wind speed at	Relative humidity %	
	Min	mean	Max	mm	9 am	3 pm	9am (Km/h)	Min	Max
2003/6/19	11	12.7	14.4	0.2	SE	SSE	12	67	79
2003/6/20	10.4	12.8	15.2	0	Calm	SSE	6	63	97
2003/6/21	8	12.35	16.7	0	NNW	WSW	16	63	98
2003/6/22	5.9	10.85	15.8	0.6	W	SSW	13	61	97
2003/11/19	20.7	30.8	40.9	2.4	N	NNW	24	21	100
2003/11/20	17.5	21.8	26.1	0	S	SSE	21	41	99
2003/11/21	14.6	18.1	21.6	0	S	SSE	26	48	75
2003/12/21	15.4	17.85	20.3	0	SSE	S	32	46	64
2003/12/22	19.4	24.05	28.7	6.4	SW	E	15	58	100
2003/12/23	21.7	25.1	28.5	2	NW	W	29	28	99
2003/12/24	12.4	17.4	22.4	0	SSW	S	23	51	78
2004/1/20	16.1	21.15	26.2	0	SE	SSE	15	31	88
2004/1/21	20.7	26	31.3	0	SSW	S	26	8	74
2004/1/22	15.6	19.75	23.9	0	S		19	53	76
2004/1/23	17.5	21.35	25.2	0	SE	SSE	23	46	66
2004/1/24	17.5	20.7	23.9	0	SSE	S	23	45	67
2004/1/25	16.9	20.4	23.9	0	S	S	19	51	75
2004/1/26	16.8	20.85	24.9	0	SSE	S	20	48	77
2004/2/22	15.4	20.25	25.1	0	SSW	SSE	16	56	97
2004/2/23	16.4	18.9	21.4	6.2	S	SSE	20	56	98
2004/2/24	16.2	20.2	24.2	0.2	ESE	S	23	44	78
2004/2/25	17.5	22.45	27.4	0	SE	S	22	33	69
2004/8/25	14.1	20.85	27.6	0	SSE	SSE	17	31	79
2004/8/26	8.7	19.4	30.1	0	NW	N	23	9	47
2004/8/27	12.1	16.95	21.8	0.8	WSW	ESE	18	11	86
2004/8/28	5	15.35	25.7	0	NNW	WNW	11	18	99
2004/8/29	7.8	17.3	26.8	0	E	N	20	21	59
2004/8/30	13.5	15.1	16.7	2	NW	NW	16	51	100
2004/9/29	9.2	11.7	14.2	1	N	WSW	24	67	98
2004/9/30	12.1	15.3	18.5	0	SSE	S	18	55	100
2004/9/31	9.1	14.35	19.6	0	SSE	S	11	53	98
2004/10/1	8.9	15.25	21.6	0	ESE	ESE	9	53	99
2004/10/2	9.9	18.9	27.9	0	NW	S	20	23	97
2004/10/3	10.9	14.85	18.8	0	SSE	SSE	14	56	82
2004/10/4	6.3	13.85	21.4	0	SSW	SE	10	48	97
2004/10/5	8.9	16.85	24.8	2.5	SSE	SE	11	31	100
2004/10/6	10.9	23.05	35.2	0	Calm	N	17	18	97
2004/11/26	20.8	30.5	40.2	0	N	NE	19	5	31
2004/11/27	26	34.3	42.6	0	N	WNW	23	4	39
2004/11/28	21.2	26.35	31.5	0	S	SSE	22	29	59
2004/11/29	22.2	28.25	34.3	0	S	S	19	22	65
2005/3/23	14.5	20.2	25.9	0	SSE	SSE	26	39	73
2005/3/24	14	19	23.9	0	SSE	SSE	24	42	81
2005/3/25	14.7	18	21.3	0	SSE	SSE	22	50	70
2005/3/26	9.3	16.6	23.9	0	Calm	SSE	17	39	89
2005/3/27	10	18.2	26.4	0	Calm	SSE	21	40	97
2005/3/28	12.2	20.2	28.1	0	SSW	SSE	17	23	98
2005/3/29	14.4	21.8	29.1	0	NNW	SSE	15	24	67
2005/4/22	7	17.5	28	0	calm	SSE	17	20	74
2005/4/23	8.6	20.3	31.9	0	NNW	SSE	11	10	69
2005/4/24	14.7	23.5	32.2	0	NNW	SSE	17	13	46
2005/4/25	17.1	19.9	22.7	0	SSE	SSE	21	40	99
2005/4/26	11.8	18.2	24.5	0	SSE	SSE	15	54	99
2005/4/27	11.4	22.3	33.1	0	NNE	SSE	9	20	92
2005/4/28	14.3	24.5	34.7	0	NNW	NNW	26	10	75
2005/4/29	17	18.3	19.5	0	SSE	SSE	28	59	98

Appendix G-1. Main land covers for indices analysis

Land covers			Image 2003/08/22	Image 2003/12/12	Image 2004/06/05
Bare ground			X		
Bare ground + Annuals [1]				X	X
Litter			X	X	X
Annuals [2]			X		
Perennials			X	X	X
BSC			X	X	X
Photosynthetic elements (Wet conditions)	Vascular plants	Perennials	X[3]		
		Annuals			
	BSC				
Photosynthetic elements (Dry conditions)	Vascular Plants	Perennials	X	X	X
	BSC				
Bare ground + BSC [4]			X	X	X

[1] In the image acquisition time of 2003/12/12 and 2004/06/05 there were no annuals, thus bare ground percentage cover was = bare ground + annuals

[2] Annual plants only in image 2003/08/22 were considered

[3] Vascular plants (annuals + perennials) only in image 2004/06/05 were considered

[4] Bare ground + BSC cover were considered if BSC are assumed as bare ground

Appendix G-2. Climatic characteristics of 11 days before image acquired on (2003/08/22). Data presented in this table were obtained from the Whyalla station, whereas in the text data were used from different stations and mostly from the MFC, thus, in some cases there are some differences between the data in this table and presented data in the text.

August days	Precipitation to 9am (mm)	Maximum Air Temperature (°C)	Minimum Air Temperature (°C)	Maximum Relative Humidity based on synoptic observations} (%)	Minimum Relative Humidity based on synoptic observations} (%)	Wind Direction at around 09:00 (9 am) (compass points)	Wind Direction at around 15:00 (3 pm) (compass points)	Average Wind Speed based on synoptic observations (km/h)	
1	10.4	18.1	7.2	99	55	NNW	N	17	
2	0.2	20.6		99	61	NNW	ESE	11	
3	4.5		11.6	100	78	WSW	SSW	14	
4	4.4	13.6	4.7	99	63	S	S	14	
5	0.1	13.9	7.5	98	48	Calm	ESE	9	
6	0	16	0.2	99	37	NNW	N	11	
7	0	21.2	3.6	98	33	NNW	W	19	
8	0	12.3		97	55	SE	SSE	17	
9	0	17.7	-0.1	83	36		NNE	12	
20	0	14.1	11.2	99	45	NNE	N	19	
21	**10**	?	**8.4**	**97**	**43**	NNW	WNW	**22**	
22	**0.2**	**19.5**	**4.8**	**99**	**37**	**Calm**	**N**	**12**	**Image acquisition day**

Appendix G-3. Climatic characteristics of 24 days before the image acquired on 2003/12/12. Data presented in this table were obtained from the Whyalla station, whereas in the text data were used from different stations and mostly from the MFC, thus, in some cases there are some differences between the data of this table and presented data in the text.

November & December days	Precipitation to 9 am (mm)	Maximum air temperature (°C)	Minimum air temperature (°C)	Maximum relative humidity based on synoptic observations (%)	Minimum relative humidity (based on synoptic observations) (%)	Wind direction at around 09:00 (9 am) (compass points)	Wind direction at around 15:00 (3 pm) (compass points)	Average wind Speed based on synoptic observations (km/h)	
18	**11.4**	36.2	20.7	99	27	NNW	NNW	18	
19	**2.4**	40.9	20.7	100	21	N	NNW	24	
20	0	26.1	17.5	99	41	S	SSE	21	
21	0	21.6	14.6	75	48	S	SSE	26	
22	0	20.3	15.4	64	46	SSE	S	32	
23	0	21.1	12.8	69	46	SSE	S	26	
24	**0.6**	22.5	13.5	80	47	SE	S	22	
25	0	28.4	11.6	98	22	S	SSE	13	
26	0	32.7	16.7	83	15	NE	ESE	15	
27	0	34.5	16.1	64	14	NNE	E	12	
28	0	34.3	18.4	53	13	N	SSE	19	
29	0	38.4		75	9		NW	20	
30	0	23.1	14.2	87	53	S	S	24	
1	0	24.3	17.8	76	51	SSE	S	26	
2	0	25.3	14.6	94	44	SSW	SSE	20	
3	0	30.2	13.8	98	38	S	SSE	18	
4	0	23.4	18	98	61	SSW	S	27	
5	**2.6**	22.2	15.6	66	44	SSE	S	28	
6	0	**23.5**	**13.6**	73	**36**	SSE	S	**22**	
7	0	**29.4**	**11.6**	**98**	**28**	S	E	**17**	
8	0	**33.6**	**17.4**	**97**	**29**	SE	E	**12**	
9	0	**44**	**16.3**	**69**	**6**	NNE	N	**27**	
10	0	**30**	**17.3**	**70**	**21**	WSW	W	**19**	
11	0	**22.6**	**11.9**	74	**50**	S	SSE	**17**	
12	**0**	**26.7**	**13.4**	**81**	**30**	**W**	**ESE**	**20**	**Image acquisition day**

Appendix G-4. Climatic characteristics of 3 days before the image acquired on 2004/06/05. Data presented in this table were obtained from the Whyalla station, whereas in the text data were used from different stations and mostly from the MFC, thus, in some cases there are some differences between the data of this table and presented data in the text.

May & June (days)	Precipitation to 9 am (mm)	Maximum air temperature (°C)	Minimum air temperature (°C)	Maximum relative humidity (based on synoptic observations) (%)	Minimum relative humidity (based on synoptic observations) (%)	Wind direction at around 09:00 (9 am) (compass points)	Wind direction at around 15:00 (3 pm) (compass points)	Average wind speed (based on synoptic observations) (km/h)	
1	16	15.5	10.9	100	83	NNW	WNW	8	
2	2	17.9	10.7	100	57	WSW	SE	10	
3	0.2	14.6	10.9	97	52	ESE	SSE	11	
4	**0**	**16**	**2**	**99**	**43**	**Calm**	**NNE**	**8**	**Image acquisition day**

Appendix G-5. The calculation of the COST model for different bands of image 2003/08/22

Band	DNmin	S. Elev.	1%	H Lmin	L1%	INPUT IN MODEL Lhaze	(Lmax-Lmin)/255	L. Min	L. Max	INPUT IN MODEL S-E Dist.	S. Exo.	INPUT IN MODEL S. Elev.
1	34	31.76	0.01	2.4433333	0.1679346	2.2753987	0.0762745	-0.15	19.3	1.0137600	195.7	31.76
2	10	31.76	0.01	1.1623529	0.1566932	1.0056597	0.1442353	-0.28	36.5	1.0137600	182.6	31.76
3	6	31.76	0.01	0.5040000	0.1333523	0.3706477	0.1040000	-0.12	26.4	1.0137600	155.4	31.76
4	1	31.76	0.01	-0.0627451	0.0889015	-0.1516466	0.0872549	-0.15	22.1	1.0137600	103.6	31.76
5	1	31.76	0.01	-0.0250118	0.0184496	-0.0434614	0.0119882	-0.037	3.02	1.0137600	21.5	31.76
7	1	31.76	0.01	-0.0084706	0.0069225	-0.0153931	0.0065294	-0.015	1.65	1.0137600	8.067	31.76

Appendix G-6. The calculation of the COST model for different bands of images 2003/08/22 (provided models for ERDAS Imagine expression in Spatial Modeler)

MODEL GMD Band1 = ((**-2.2753987** + (**0.0762745** * $n1_gb_tm_or(1) - **0.15**)) * PI * **1.0137600** ** 2) / (**195.7** * COS (PI/180 * (90 - **31.76**)) ** 2)
MODEL GMD Band2 = ((**-1.0056597** + (**0.1442353** * $n1_gb_tm_or(1) - **0.28**)) * PI * **1.0137600** ** 2) / (**182.6** * COS (PI/180 * (90 - **31.76**)) ** 2)
MODEL GMD Band3 = ((**-0.3706477** + (**0.1040000** * $n1_gb_tm_or(1) - **0.12**)) * PI * **1.0137600** ** 2) / (**155.4** * COS (PI/180 * (90 - **31.76**)) ** 2)
MODEL GMD Band4 = ((**0.1516466** + (**0.0872549** * $n1_gb_tm_or(1) - **0.15**)) * PI * **1.0137600** ** 2) / (**103.6** * COS (PI/180 * (90 - **31.76**)) ** 2)
MODEL GMD Band5 = ((**0.0434614** + (**0.0119882** * $n1_gb_tm_or(1) - **0.037**)) * PI * **1.0137600** ** 2) / (**21.50** * COS (PI/180 * (90 - **31.76**)) ** 2)
MODEL GMD Band7 = ((**0.0153931** + (**0.0065294** * $n1_gb_tm_or(1) - **0.015**)) * PI * **1.0137600** ** 2) / (**8.067** * COS (PI/180 * (90 - **31.76**)) ** 2)

Appendix G-7. Land covers used for correlation with image data in images 2003/08/22

Sites	Bare Ground (%)	Litter (%)	Perennials (%)	Annuals (%)	BSC (%)	Vascular plants (%)	Total photosynthetic elements (%)	Total dry photosynthetic elements (BSC + perennials) (%)
Balah _100	58.75	13.2	20	7.90	0.15	27.9	28.05	20.15
Balah _660	64.17	15.3	9.67	1.10	9.76	10.77	20.53	19.43
Balah _1300	57.98	10.8	7.77	0.00	23.45	7.77	31.22	31.22
Balah _2000	45.24	12.02	22.96	0.00	19.78	22.96	42.74	42.74
Balah _2800	48.23	4.4	9.42	0.90	37.05	10.32	47.37	46.47
Balah _4000	26.12	10.02	15.96	1.80	46.1	17.76	63.86	62.06
Billabong _100	61.06	9.08	12.45	14.90	2.51	27.35	29.86	14.96
Billabong _660	60.46	4.53	15	0.95	19.06	15.95	35.01	34.06
Billabong _1300	59.5	5.31	14.61	0.03	20.55	14.64	35.19	35.16
Billabong _2000	58.16	7.12	8.61	0.00	26.11	8.61	34.72	34.72
Billabong _2800	37.92	11.2	18.75	0.00	32.13	18.75	50.88	50.88
Billabong _4000	34.03	9.01	17.99	0.10	38.87	18.09	56.96	56.86
Corio _100	75.6	3.12	19.78	1.48	0.02	21.26	21.28	19.8
Corio _660	54.23	4.86	16.21	0.17	24.53	16.38	40.91	40.74
Corio _1300	68.45	1.76	14.45	2.34	13	16.79	29.79	27.45
Corio _2000	47.38	8.14	6.66	0.00	37.82	6.66	44.48	44.48
Corio _2800	48.01	4.67	10.87	0.05	36.4	10.92	47.32	47.27
Corio _4000	46.43	4.79	14.27	0.07	34.44	14.34	48.78	48.71
Purpunda_100	46.44	12.6	19.98	15.94	5.04	35.92	40.96	25.02
Purpunda_660	49.69	9.04	23.36	1.15	16.76	24.51	41.27	40.12
Purpunda_1300	31.59	7.71	20.5	12.47	27.73	32.97	60.70	48.23
Purpunda_2000	33.56	8.11	13.17	0.00	45.16	13.17	58.33	58.33
Purpunda_2800	27.31	9.37	32.41	0.63	30.28	33.04	63.32	62.69
Purpunda_4000	33.24	13.57	28.63	0.60	23.96	29.23	53.19	52.59
Railway _100	66.21	8.29	10.92	13.48	1.1	24.4	25.5	12.02
Railway _660	63.77	11.6	16.6	3.90	4.13	20.5	24.63	20.73
Railway _1300	46.4	10.4	14.85	1.67	26.68	16.52	43.2	41.53
Railway _2000	44.85	11	13.9	0.08	30.17	13.98	44.15	44.07
Railway _2800	46.09	12.04	15.86	1.66	24.35	17.52	41.87	40.21
Railway _4000	39.88	15.86	8.22	0.80	35.24	9.02	44.26	43.46

Appendix G-8. Land covers used for correlation with image data in images 2003/12/12 and 2004/06/03

Sites	Bare Ground (%)	Litter (%)	Perennials (%)	BSC (%)	Total dry photosynthetic elements (BSC + Perennial) (%)
Balah _100	66.65	13.2	20	0.15	20.15
Balah _660	65.27	15.3	9.67	9.76	19.43
Balah _1300	57.98	10.8	7.77	23.45	31.22
Balah _2000	45.24	12.02	22.96	19.78	42.74
Balah _2800	49.13	4.4	9.42	37.05	46.47
Balah _4000	27.92	10.02	15.96	46.1	62.06
Billabong _100	75.96	9.08	12.45	2.51	14.96
Billabong _660	61.41	4.53	15	19.06	34.06
Billabong _1300	59.53	5.31	14.61	20.55	35.16
Billabong _2000	58.16	7.12	8.61	26.11	34.72
Billabong _2800	37.92	11.2	18.75	32.13	50.88
Billabong _4000	34.13	9.01	17.99	38.87	56.86
Corio _100	77.08	3.12	19.78	0.02	19.8
Corio _660	54.4	4.86	16.21	24.53	40.74
Corio _1300	70.79	1.76	14.45	13	27.45
Corio _2000	47.38	8.14	6.66	37.82	44.48
Corio _2800	48.06	4.67	10.87	36.4	47.27
Corio _4000	46.5	4.79	14.27	34.44	48.71
Purpunda_100	62.38	12.6	19.98	5.04	25.02
Purpunda_660	50.84	9.04	23.36	16.76	40.12
Purpunda_1300	44.06	7.71	20.5	27.73	48.23
Purpunda_2000	33.56	8.11	13.17	45.16	58.33
Purpunda_2800	27.94	9.37	32.41	30.28	62.69
Purpunda_4000	33.84	13.57	28.63	23.96	52.59
Railway _100	79.69	8.29	10.92	1.1	12.02
Railway _660	67.67	11.6	16.6	4.13	20.73
Railway _1300	48.07	10.4	14.85	26.68	41.53
Railway _2000	44.93	11	13.9	30.17	44.07
Railway _2800	47.75	12.04	15.86	24.35	40.21
Railway _4000	40.68	15.86	8.22	35.24	43.46