Effects of Soil Crusts on the Erodibility of a Claypan in the Channel Country, South-West Queensland, Australia.

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Abstract

This thesis explores the role of cyanobacterial crusts in controlling the aeolian erodibility of arid soil surfaces. Soil erodibility estimates are commonly derived from sediment trap measurements or field wind-tunnel simulations. Such estimates are often difficult to relate to crust types and conditions because of the intricate spatial variation inherent with crusts. Similarly, empirical wind-erosion models across a range of spatial scales often fail to incorporate a crust parameter simply because of the complexity associated with both spatial and temporal variations in crustal attributes.

The soils of the Channel Country, western Queensland, the site of this study, have intricate mosaics of biological and physical crusts. These arid soils are frequently affected by wind erosion and the role that the presence of the crusts has in controlling erodibility is a largely unknown. The aim of this study has been to address this knowledge gap.

It was found that the spatial heterogeneity of the surface features described for the study area claypan supported a diverse range of crust types and cover levels. This diversity varied at sub metre increments. Such spatial diversity is beyond the sensitivity of most common measurement or modelling approaches used in wind erosion research. To overcome this, a specialised Micro Wind Tunnel (MWT) was developed providing a reliable and practical solution measuring erodibility between different crust types. The MWT successfully provided laminar horizontal airflow with and without added saltation material, to specific crust types. Importantly, the size of the MWT was appropriate to the spatial heterogeneity of crust types.

The concept of erodibility therefore is often confused and in attempt to breakdown this confusion terminology was revised and the erodibility was defined. The concept of Erodibility was defined as the susceptibility of a soil to erosion. However extremely important though is that there is erodibility inherent to the soil – soil erodibility (E_{soil}) and to the soil surface – surface erodibility (E_{surface}). Each interact with each other to produce overall erodibility.
Erodibility Characteristics: Both the soil and the soil surface have inherent characteristics which contribute to the overall erodibility. Therefore erodibility characteristics should be viewed AND reported as both soil erodibility characteristics ($E_{\text{soil}}$) and surface erodibility characteristics ($E_{\text{surface}}$).

Erodibility Output Measures: A number of measurement instruments are used to quantify the amount of sediment lost from a site during erosion, for example, wind tunnels, sediment samplers and even wind erosion event frequencies. The units of their measurement form the erodibility output measures, e.g. sediment flux, sediment concentration and dust storm frequency. The erodibility output measures are ‘blunt’ tools (usually a number) which whilst quantifying the overall erodibility do not and can not partition the erodibility characteristics controlling the current erodibility status.

The environmental histories of each crust surface indicated that where similar conditions were experienced it was the type of crust present which determined the fate of any environmental disturbance. It is suggested that rather than being discrete crust features belonging to either physical or biological taxonomic descriptions, the crusts belonged to a crust continuum. The impacts of time, climate and disturbance alter the properties of the soil surface, allowing the crusts to either:

- develop into diverse biological crust forms in response to favourable growing conditions; or
- regress towards physical crusts after unfavourable growing conditions or high disturbance.

Cyanobacteria crusts feature strongly in claypan erodibility. A significant property of these crusts is that they are living organisms, responding to changes in weather. Rainfall was found to be an important controlling factor to growth. Cyanobacteria were found to reside at depth in the soil profile until sufficient moisture was received. Small rainfall events, less than 4 mm, however were sufficient to initiate metabolic activity causing surface greening. Regularly high solar radiation returned quickly restricting activity, causing the cyanobacteria to retreat deeper in the soil profile. It was proposed that this water-solar radiation relationship could have two major implications following small rainfall events;

- cyanobacteria respond metabolically but have insufficient moisture to sustain growth. This results in either desiccation or sub-surface retreat leaving the soil
surface, at a micro scale, disturbed and loose, potentially increasing the erodibility after rainfall; or

- insufficient moisture inhibits the full suite of metabolic functions; reactivation, photosynthesis, physical filament development, nitrogen fixation and reproduction.

The cyanobacteria use its energy stores to initiate these processes but with declining moisture and increasing solar radiation (commonly associated with small rainfall events), desiccation is forced. Infrequent small rainfall events therefore weaken the cyanobacteria crust potentially increasing the erodibility of the soil to wind erosion.

Moisture dependencies such as these pose questions for the long-term stability of crusted surfaces in the face of changing rainfall patterns as predicted by climate-change models for Australia. A decrease in the frequency of larger rainfall events may have the potential to leave the cyanobacteria biological crusts weaker, decreasing their resistance to disturbance, thereby increasing the erodibility of the soil. These conditions would result in an increased instance of wind erosion.

Disturbance of biological crusts leads to the entrainment of sediment and cyanobacteria. Quantitative analysis reveals that cyanobacteria filaments are capable of being transported throughout the claypan. As these filaments are light, small and buoyant, they can be held aloft and transported beyond the source area. Biological material was collected in a sediment trap at a height of ten metres. At this height, the sediment is above the natural boundary layer, making the filaments available for transport beyond the immediate area.

This thesis has confirmed the important role that cyanobacteria crusts have in governing the erodibility of Channel Country soils. The research results have new implications for the geomorphology of cyanobacterially crusted areas due to crust response to rainfall. Ecologically, the potential long range distribution of cyanobacteria filaments presents interesting thoughts regarding colonisation and landscape stability. By directly affecting crust development and recovery, variations in rainfall patterns induced by climate change will have important implications to ecological and geomorphic systems of the semi-arid regions of Australia in coming years.
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Chapter 1. Introduction, Background and Thesis Structure

1.1 Wind erosion in Australia

On 23 October 2002 a large frontal system passed over extensive areas of drought-stricken inland Australia, creating an enormous dust storm (Figure 1.1). The significance of this event was firstly its spatial extent: ninety percent of eastern Australia experienced either a wall of dust or a dust haze. An estimated 4.85 million tonnes of sediment became airborne and a large proportion was deposited off-shore in the Pacific Ocean (McTainsh et al., 2005). Such quantities of lost sediment also represent a massive amount of nutrients lost from the source areas.

Events of this magnitude are significant not only from a land degradation perspective, but also from a social one. As Diamond (2005) points out, there is an alarming trend for Australians to become detached from their landscape. They do not depend on or 'really' live in the Australian environment; rather, they live in big coastal cities with more connections to the outside world. When a major dust storm affects a coastal city, its residents are forced to acknowledge that they live on the edge of the driest continent on earth.

The October 2002 event did just that, and during the following years a large number of dust events passed over coastal cities. Each time, a flurry of media attention was generated, focusing on the stripping of topsoil from drought-ravaged farms, the continuing misfortune of struggling farmers, or the hospitalisation of residents suffering respiratory problems.

Yet land degradation issues, such as wind erosion, remain on the periphery of public consciousness. Despite the spectacular nature of major dust storms, the public perceive these events as an occasional nuisance. A quick review of the literature demonstrates that they are certainly more than ‘occasional’ and describing them as a ‘nuisance’ understates their very real impact. In reality, wind erosion is responsible for the loss of fine particles and nutrients from soils, damage to infrastructure and stock via burial, destruction of crops from the saltation of coarse particles, and serious health issues for many Australians (Williams and Young, 1999).
1.2 Dust transport and deposition in Australia

In Australia, dust activity is concentrated in the semi-arid and arid regions, with pronounced seasonal fluctuations in intensity in response to variable rainfall. Australian dust storms are the product of high erosion rates of semi-arid and arid land, depositing sediment across lands downwind (Cattle et al., 2006) and into neighbouring oceans (Boyd et al., 2004). Within Australia, there are two major dust transport paths: the north-west dust path which passes off the northern coast of Western Australia; and the better-studied south-east path. Originally, Bowler (1976) formulated a model of dust transport based largely on the semi-circular orientation of
the dunefields in Australia. This was supported by the meteorological collections of Sprigg (1982) who was able to show that the dune fields were developed by regular weather patterns crossing the continent. These dust paths have since been supported by present day dust-storm activity and related processes (McTainsh, 1989).

Soils of many global dust source areas show evidence of dust deposition. In contrast with China, Australian desert margins are not bordered by high-relief and humid climates where deposited dust forms easily-identified loess soils (Pye and Tsoar, 1990). Only relatively recently, however, has fingerprinting of dust within eastern-Australian soils shown that aeolian dust has been deposited at rates sufficient to form (Cattle et al., 2001), and make important nutrient contributions to, soil over large areas of eastern Australia (Hesse and McTainsh, 2003).

There is both Quaternary and contemporary evidence of dust deposition in the Pacific and Indian Oceans. Sedimentological studies show strong correlations between the mineralogy of Australian dusts transported on the south-east and north-west pathways (Kiefert, 1995) and sediments in the south-west Pacific and north-east Indian Oceans (Griffin et al., 1968).

Meteorological records of dust activity show that the Simpson Desert–Channel Country region of the Lake Eyre Basin has the highest annual frequency of dust storms in Australia (McTainsh et al., 1990, McTainsh et al., 1999). On average, twenty-three dust storms per year were reported for this region from 1960 to 1996 (McTainsh et al., 1999). Many of these events remove enormous quantities of sediment from the region. For example, Knight et al., (1995) estimated a soil loss of 5.5–6.3 million tonnes from a 100,000–200,000 km² area of the Simpson Desert-Channel Country region alone in December 1987, and McTainsh et al., (1996) estimated that some 15 million tonnes of dust were moved from the Channel Country in a single event in November 1994.

The magnitude of such dust storms has lead to estimates of annual sediment loss via dust storms for the Simpson Desert-Channel Country region alone in excess of 120 tonnes/km² (Knight et al., 1995). When compared with the estimated 37–45 tonnes/km² annual sediment discharge of Australian rivers, it is easy to see that a staggeringly higher amount of sediment is ‘exported’ from the continent in the air.
than in the rivers. Wind erosion in Australia is, therefore, more than an occasional nuisance.

Yet, in geomorphic terms, the tangible evidence left by dust entrainment and deposition is cryptic compared to the geomorphic ‘billboards’ of dune fields and river systems (Goudie, 1978; McTainsh, 1989). The subtleness of these aeolian processes has often meant that the significance of individual events (with the exception of major events like those discussed above) goes unnoticed. A growing awareness of the importance and scale of dust activity has come largely with advancing technologies. The advent of satellite monitoring techniques has lead to both an enhanced understanding of where the global hotspots are (Prospero et al., 2002) and sometimes-confronting images of the spatial impact that they have (Figure 1.1).

### 1.3 Wind erosion processes—dust entrainment

The phenomenon of wind erosion is most often perceived as the transportation and deposition of dust. Dust is comprised of both mineral and biological materials less than 70 µm in diameter (Pye, 1987). In order to be transported, however, dust particles must first be entrained—the processes by which soil particles are moved from their original position. Dust entrainment is a complex dynamic process relying on two general interacting controls:

- The erosivity of wind
- The erodibility of a soil surface

These controls are complex and vary continuously through space and time.

Erosivity can be defined as the capacity of wind to entrain soil particles from the soil surface (Bagnold, 1941). As wind blows across a soil surface, frictional forces act on it, steeply reducing wind velocity near the ground surface. This is compounded by surface irregularities, or roughness. The wind velocity at the roughness interface is termed the ‘friction velocity’ ($u_*$) and the height of the layer, the ‘roughness height’ ($z_0$). The erosivity of the wind can be best described by the shear stress exerted at this interface, and is therefore also related to the friction velocity. It was Bagnold (1941) who noted that particles did not move until a given friction velocity ($u_*$) was reached.

Movement of soil particles can occur through either:
The force of wind alone (i.e. without impact from other grains), known as the fluid threshold ($u_f$)

• Impact from other grains, known as impact threshold ($u_i$)

Although there are significant differences between these two measures, it is very difficult to measure them independently in the field. Nickling (1988), therefore, proposed that threshold velocity ($u_t$)—the velocity at which the whole soil surface starts to move—is a better measure.

As erosivity is related to the frictional velocity, any alteration in wind speed and/or surface condition will alter erosivity. Controlling factors such as these pose particular difficulties when measuring field conditions. In field experiments, changes in both wind speed and direction can be measured at large spatial scales, but pose difficulties at smaller local scales.

The greatest challenge to understanding wind erosion, however, is determining how changes in erosion rates relate to the spatially diverse soil-erodibility factors. Erodibility is defined as the susceptibility of the soil surface to erosion by wind (Bagnold, 1941). Experimental studies carried out using both wind tunnels and field conditions have identified many factors that affect the erodibility of a soil surface (Bagnold, 1941; Chepil and Woodruff, 1963; Gillette et al., 1980,1982; Nickling and Gillies, 1993; Nickling et al., 1999). These include:

• vegetation and surface roughness
• soil texture
• soil moisture
• soil binding agents, both mineral (e.g. CaCO$_3$) and organic (e.g. polysaccharides)
• particle-size
• particle shape (Greeves and Leys, 1999)

These factors are time dependent and should be considered as a continuum rather than a single point measure (Leys et al., 1996). As these properties change through time they influence other factors such as soil aggregation and soil crusting (both physical and biological).
A soil’s erodibility can be measured in a variety of ways, including:

- Measurement of a soil characteristic known to influence a soil’s erodibility to
  wind, such as dry aggregation >0.85mm (Leys et al. 1996)
- Measurement of soil loss using sediment traps (Shao et al., 1993)
- Wind tunnel simulations (Leys and Raupach, 1991) which are then related to soil
  erodibility characteristics.

Whichever method is used, it is important to view the measure in the context of its
time and spatial scale.

Significant advances in understanding wind erosion have come from modelling
exercises, but the limited understanding of underlying processes (such as erodibility
controls) on wind-erosion rates has hampered development of these models. As
highlighted above, the soil-surface features that control erodibility are numerous,
variable in both time and space, and often interact. Using a modelling approach, this
complexity is usually reduced to a single value. As a result, modelled values are often
poorly constructed with measured values. Realizing these limitations, modellers are
calling for more ‘input data’, and in particular a better understanding of the
controlling mechanisms of erodibility. One key unknown is the complex influence of
soil-surface crusts.

### 1.4 Soil crusts

Soil crusting arises from changes in the physical, chemical and biological
characteristics of a soil surface. Depending on the formation processes, the crust can
vary in thickness from less than a millimetre to a few centimetres, and can have a
different biological content and particle size from the soil surface beneath.

Soil surface crusting encompasses a diverse range of forms, distributions and
persistences in the landscape. Such diversity poses problems for both modellers and
field researchers because generalisations can not be made about how soil crusts
influence rates of wind erosion. Specific knowledge of each crust type is required to
understand the impacts on wind erosion and other landscape functions. For example,
wind erosion researchers frequently treat all smooth surfaces as a single type of
erodibility feature. In reality, this surface type could comprise up to a dozen different crust types, each with their own erodibility.

The crust type that will receive particular attention in this thesis is the cyanobacteria crust, a specific type of biological crust. Investigations of biological soil crusts are comprehensive in some areas, yet limited in others. The larger, more conspicuous species, such as mosses and lichens, have received greatest attention, while the cyanobacterial and algal crusts have often been overlooked due to their small, cryptic nature. This does not, however, reflect the relative abundance of these soil taxa, with cyanobacterial crusts abundant throughout the hot arid and semi-arid regions of the world, and Australia in particular. Research into cyanobacterial crusts has often been laboratory-based using cultured samples (see Chapter 7 for a review of these studies). This laboratory approach can lose sight of the fact that these crusts are complex, responding to environmental triggers and evolving through time.

1.5 Erodibility and biological crusts

The influence of biological crusts on soil erodibility relates to the modification of three soil properties:

- Changes in surface roughness induced by biological crusts increase the threshold velocities required to initiate sediment movement. Both field studies (Leys and Eldridge, 1998) and laboratory studies (McKenna Neuman and Maxwell, 1999) have shown that micro-topographic roughness is sufficient to induce increases in threshold velocities.

- Biological contributions to soil aggregation have been found to increase soil stability (Aspiras et al., 1971; Bailey et al., 1973; Degens, 1997). Two biological processes contribute to the increased levels of aggregation: first, soil particles are stabilised into macro-aggregates through physical binding or entanglement by hyphae and roots; second, exocellular polysaccharide secretions produced by some crusts species diffuse away from the cells into the surrounding environment, resulting in aggregation of soil particles (Lynch, 1981; Hepper, 1985; Schulten, 1985; Maxwell and McKenna Neuman, 1994).

- Biological crusts modify the surface strength via physical and chemical binding. This property is alluded to through experimental work using penetrometers (Rice
and McEwan, 2001) and through disturbance experimentation (Booth, 1941; Rice et al., 1996; Leys and Eldridge, 1998).

1.6 Thesis rationale and structure

The influence of biological crusts on soil erodibility draws on research from around the world, highlighting the significance that wind erosion and biological crusts have on a global scale. One third of the world’s land surface is classified as dryland, where annual potential loss of moisture from evapotranspiration well exceeds the moisture received as rainfall. Large areas of central Asia, south west USA, southern America, Arabia and much of Africa experience desert characteristics. As such, all suffer the impacts of wind erosion and all have biological crusts. Therefore any improvements in understanding the role of biological crusts on the soil erodibility in Australia will have direct significance to each of these other drylands.

The Australian continent however provides a valuable platform for studying and understanding the role of biological crusts, and specifically cyanobacterial crusts, in wind erosion. More than 70 percent of Australia receives, on average, less than 250 mm annual rainfall (Eldridge, 1998), and these areas also experience some of the highest wind-erosion rates (McTainsh et al., 1990). Importantly, cyanobacterial soil crusts dominate much of the arid and semi-arid soils, the source of most aeolian sediments. It was, however, the discovery that up to 60 percent of Australian dust is composed of organic matter (Boon et al., 1998) that has been a key driver of this study, as it suggested a connection between biological soil crusts and wind erosion in Australia. Having worked in the landscapes where these figures were sourced, I could not help but question where this biological matter came from.

Claypans (playas) are wind erosion hotspots in Australia (McTainsh, 1999). Vegetation on the claypans is sparse and Australian soil organic-matter levels are low, posing the conundrum: how does dust become enriched with organic matter? Claypan surface soils are, however, enriched with cyanobacteria. These cyanobacterial crusts can hold the soil together, and can turn the soil surface green after rainfall. Whether it was possible that the cyanobacteria could contribute so significantly to the organic-matter content of Australian dust was the original question that this study hoped to answer.
Once this study began, however, the limited understanding of the role of biological crusts on wind erosion in Australia quickly emerged. Initially, the research questions for this thesis were quite specific, but the scarcity of research on cyanobacterial crusts in Australia had major implications for the direction of the thesis. The following limitations were identified:

• There is limited quantitative information on the effect of biological soil crusts on the erodibility of soils to wind erosion in Australia.

• Available research results are:
  – principally from overseas
  – location specific
  – crust-morphology specific; and
  – generally biased toward one of the disciplines (i.e. aeolian geomorphology or landscape ecology).

• There is a scarcity of wind-erosion research investigating cyanobacterial crusts in Australia.

• Only a few overseas studies of cyanobacterial ecophysiology in the field exist, with these being lithophytic cyanobacteria species (Budel et al., 1997, 1999; Rascher et al., 2003). No Australian research exists and worldwide research into desert cyanobacteria crusts has been limited.

• Independently, aeolian geomorphology and landscape ecology are discrete research disciplines, each with their own research hypotheses, methodologies and conundrums. Addressing the role of cyanobacteria in controlling wind erosion requires a cross-disciplinary approach not commonly undertaken.

In effect, it become apparent that to answer only the original organic matter question would be putting the cart before the horse. This thesis aims to provide more fundamental evidence of the interactions between soil surfaces on claypans—in particular cyanobacterial crusts—and wind erosion.

I have taken a top-down approach and started with a general question: what are the relationships between landscape elements and the erodibility of Channel Country soils to wind? From this point, I investigate the drivers affecting the erodibility of biological crusts and the cyanobacteria that often make them up. Channel Country
soils were selected for study, as they are a known source of major wind erosion and often contain biological crusts.

At the outset, four major assertions were made with respect to erodibility of Channel Country soil surfaces:

- The soil-surface landscape of a typical claypan is diverse, which is reflected in a spatial and temporal diversity of erodibility across the claypan.
- Using a number of measurement techniques provides a more useful measure of erodibility due to the diversity of elements that make up the soil surfaces typically found on a claypan.
- Biological crusts will reduce the erodibility of a soil surface.
- Cyanobacteria are entrained by wind-erosion activity.

These assertions were tested through the following research objectives:

- To investigate the types and spatial distribution of soil-surface types on a claypan of the outer floodplain of the Diamantina River.
- To develop appropriate methodologies for measuring the wind erodibility of small patches of variable soil surfaces.
- To determine the erodibility of different soil-surface types on a claypan.
- To improve understanding of the cyanobacterial response to fundamental environmental factors, including:
  - hydration (i.e. rainfall)
  - light (i.e. solar radiation); and
  - nutrients.
- To identify how different surface types react to variable weather conditions through time to produce a dynamic claypan surface.

The structure of this thesis follows this top-down approach (Figure 1.2). The first section (Chapters 1 to 4) provides important background information, including:

- a description of the study area
- the methods used throughout the study; and
• a detailed review of the development and testing of a new instrument to measure erodibility.

The second section devotes itself to understanding the erodibility of the claypan surface. This is done by first profiling the diversity of soil surfaces on the claypan (Chapter 5), and then quantifying the erodibility of four field sites using multiple methods (Chapter 6). Each soil surface tested for erodibility encompasses considerable variety within itself, both in time and space. In order to better understand these variations, one soil-surface type—biological soil crusts—is studied at a finer resolution. In particular, the ecophysiology of cyanobacterial crusts is examined in an attempt to appreciate how the organisms survive and modify the rates of wind erosion (Chapter 7).

The final section of the thesis returns to the original question: can cyanobacteria be transported by wind, and is this the likely cause of high organic matter in dust sediment? Using the knowledge gained in the previous chapters, I postulate a conceptual model of how the cyanobacterial crusts function in the claypan landscape and the impact they have on soil erodibility (Chapter 8). A component of this claypan landscape functionality is the entrainment of cyanobacterial crusts. Entrainment of cyanobacteria and subsequent transport within the claypan boundaries is explored with the intention of identifying the potential of cyanobacterial crusts to contribute to the organic enrichment of dusts. Chapter 9 examines future research directions and provides a summary of the thesis.
Figure 1.2. Schematic of the thesis structure

Section I. Thesis Background
- Chpt. 1: Introduction
- Chpt. 2: Study Area
- Chpt. 3: Methodologies
- Chpt. 4: Development of a micro wind tunnel

Section II. Crust erodibility: "What is there, how to measure and what is erodible?"
- Chpt. 5: Spatial patterns of soil surfaces
- Chpt. 6: Relative erodibility of crusts

Section III. Cyanobacteria crusts: "How do they survive in such a harsh environment and what does this mean to wind erosion?"
- Chpt. 7: Ecophysiology of cyanobacteria crusts

Section IV. Holistic model of cyanobacterial crusts on the claypan:
- Chpt. 8: Spatio-temporal perspectives of claypan erodibility

Section V. Summarizes the results, highlights the significance of the research and lights the path to future work.
- Chpt. 9: Future research directions and summary
Chapter 2. Study Area

2.1 Introduction

Dust source regions in Australia include:

- dune fields
- alluvial floodplains
- grassy downs country; and
- salt-impacted scald regions.

Combined, the Simpson and Strezlecki dune fields—both within the Lake Eyre Basin—form the largest dust source area in Australia, encompassing over 510,000 km$^2$ of linear dunes. The Lake Eyre Basin consists of a network of internally draining river systems, terminating at Lake Eyre in South Australia. Three major rivers, the Georgina, Diamantina and Cooper, flow from low-latitude humid regions in Northern Australia to the arid centre. These rivers encompass a vast network of alluvial floodplains, and although they flow infrequently, they have the capacity to carry vast quantities of sediment. The low gradient of the rivers results in multi-channelled river beds and wide floodplains. These characteristics form ideal conditions for the deposition of sediments destined to be entrained as dust. Known as the Channel Country, these alluvial floodplains are equally important Australian dust source areas as the dune fields.

Anthropogenically modified landscapes, such as rangelands and broad-acre cropping areas, have accelerated the rate of wind erosion in many instances. These areas of anthropogenically-enhanced dust emissions have been the subject of urgent attention in an attempt to minimise further impacts (Leys, 1999). The natural dune fields and alluvial floodplains of the Channel Country, however, have received little attention. This is due in equal parts to a perception that their impact is only felt by a small proportion of the population and an acceptance that these areas ‘should be dusty’. These areas do represent a very significant contribution to the total Australian dust emission and do, in truth, make a considerable contribution to the overall impact of wind erosion on Australia. In addition to being a major dust source, the Channel Country presents an opportunity to understand the relationship between biological soil
crusts and wind erosion. For these reasons, it was the focus of all field studies that make up this thesis.

In order to meet the primary aim of this thesis—to better understand the erodibility of soil surfaces on a claypan—it is essential to provide an environmental profile of the study area. Various environmental influences contribute to our understanding of the behaviour of the claypan surface in the following ways:

- Landforms and soils provide information about the environment in which the biological crusts grow and physical crusts form.
- Rainfall and solar radiation provide a picture of the physical stresses that are imposed on the growth of all biological life.
- Flood frequency affects not only available water, but also sediment and nutrients.
- Meteorological conditions characterise the potential wind magnitude and direction.
- Vegetation has many important functions:
  - It acts as an overall wind-erosion suppressor.
  - It contributes organic matter to the soil.
  - It has the capacity to change the texture and chemical properties of soil.

### 2.2 Study location and description

The study area is located within Diamantina National Park (DNP) in the Channel Country of SW Queensland, approximately 350 km NNE of Birdsville and 1,800 km WNW of Brisbane (Figure 2.1). DNP encompasses all the main land features that characterise the Channel Country and much of the Australian arid zone (McTainsh et al., 1999). These include dune fields, floodplains, claypans and downs country.

The Channel Country is so called because of its vast network of low-gradient, intermittently-flowing channels. During dry periods, the channels consist of a series of dry creek lines with ephemeral and permanent waterholes (billabongs). In flood, however, the creeks quickly overflow their banks, forming a large ‘sheet’ or river of water. In some areas this river can be tens of kilometres across. At its widest point in full flood, the Diamantina River is wider than the English Channel.
Claypans occur on the outer floodplain of the Diamantina River. Wind-erosion rates are greatest on these claypans, compared to the downs and dunes (McTainsh et al., 1999). These outer floodplain regions are only submersed under floodwater during extreme flood events, providing the claypans with an infrequent supply of sediment.

Surface characteristics of the Channel Country claypans predispose them to wind erosion. These characteristics include:

- low vegetation cover
- high alluvial deposition rates
- heterogenous cover of both physical and biological crusts; and
- a supply of aeolian saltation material.

The frequency of wind erosion and the diversity of surface features, including the occurrence of cyanobacterial crusts on the claypans, meant it was the logical place to conduct this research.
2.3 Land forms

2.3.1 Geological history
The Channel Country makes up the north-eastern section of the Lake Eyre Basin, and contributes large quantities of sediment to this internally-draining basin (Bullard and McTainsh, 2003). The modern Lake Eyre Basin lies on the eastern edge of the Australian craton, and was formed from tectonic movements in the Mesozoic (Wopfner and Twidale, 1967). The Mesozoic was marked by the deposition of a number of sedimentary formations, including marine sandstones, mudstones and shales. The Cretaceous Period saw the transition from marine to freshwater deposition, and laid down much of the important surface geology seen throughout the region today. The Wilginya Beds formed in a marine environment, the Mackunda...
Beds in the transition (brackish waters), and the *Winton* Formation in a freshwater environment (post-regression) (Croke *et al.*, 1998).

These Cretaceous beds were exposed to gentle uplift, and during the Tertiary were weathered in laterite and siliceous duricrusts ranging from 0.5–3.0 m (as were other rocks ranging from Proterozoic to lower Tertiary across much of the Lake Eyre Basin) (Wopfner and Twidale, 1967). Petrographic analysis of these duricrusts reveals the following components (Wopfner and Twidale, 1967):

- medium to fine-grained quartz fixed within a micro to cryptocrystalline siliceous matrix
- a zone of brilliant white kaolinite with minor illite and smectite; and
- a brittle ferruginous zone of haematic shale and sandstone interbedded in kaolinite material.

In essence, the mid-late Cainozoic surface geology of the Great Artesian Basin consisted of a range of Cretaceous and Tertiary sediments capped by laterised and siliceous duricrust surfaces.

During the late Oligocene to early Miocene, epeirogenic movements centred in the Lake Dieri (Pleistocene ancestor of Lake Eyre) region induced warping of the brittle duricrust, causing fracturing of these surfaces over large areas of the Lake Eyre Basin. These tectonic movements also initiated the uplift and exposure of the underlying Cretaceous sediments in the Channel Country region. These rocks were tilted in a south-west direction, initiating a new cycle of erosion and alluvial transportation of pre-existing Tertiary duricrusts and Cretaceous sediments (Dulhunty, 1983). This ultimately transported vast-quantities of sand and mud to the Channel Country rivers through the mid to late Cainozoic (Simon-Coincen *et al.*, 1996).

### 2.3.2 Modern landforms of the Channel Country

The geological history described above has produced the distinctive landforms that characterise the Channel Country. These include floodplains, claypans, longitudinal dunes and downs country. The floodplains have developed into an involved and complex series of interlaced stream branches in valleys whose silt floors slope at gradients of 170 mm/km (White, 2001).
Different stream morphologies exist across and along the length of the Channel Country Rivers. Shallow braid-like channels separated by levees and broad, low-relief bars exist on the outer edges of the rivers. These channel types sit on top of a surface of highly-variable, clay-rich, heavily-cracked floodplain (Maroulis and Nanson 1996) and flow during high flood events (Rust and Nanson, 1986). Anastomosing channels, inset within the floodplains at depths of up to 7 m (Gibling et al., 1998), are generally operational during both moderate and high flows. Deeper channels form near permanent waterholes and have been incised into the underlying sand body (Nanson et al., 1986), forming the main channels.

The sediment mineralogy of the Channel Country rivers produces a significant attribute: the transportation of clay-rich sand-sized particles (or pellets) of low density and high durability. These pellets can be entrained as bedload and are transported mainly by the high-energy leading edge of the flood wave (Maroulis and Nanson, 1996). Overbank deposition of these aggregates influences the surface features of the outer floodplains.

Claypans are regular features on the outer floodplains of the Diamantina River. These are deflation hollows characterised by relatively smooth, variably-crusted surfaces which seal rapidly with hydration. They differ from salt lakes in that the groundwater table is deeper, preventing the formation of evaporative salt crusts at the surface (Mollemans et al., 1984). The outer floodplains require a major flood for inundation to occur. At DNP, this occurs, on average, once every three or four years with local flood stage readings greater than 4.8 m. A combination of low rainfall, flood frequency and surface conditions restrict vegetation growth in general. This absence of vegetation, combined with the deposition of sediment during floods, makes claypans active wind-erosion landforms.

Dunefields occur throughout the Channel Country and represent a previous geological transportation phase. These dunefields are composed largely of quartzose sands originating from the Mt Isa and Charters Towers regions and transported to their present positions by a complex process of alluvial and aeolian action (Gregory et al., 1967). Many dunes have a partly-consolidated core with a higher percentage of clay compared to the outer dune surface. Contemporary conditions are conducive to
vegetation growth along the lower to mid dune flanks. The crests generally remain bare and longitudinal movement of sand along the dune can often be observed.

The downs area is comprised of large areas of flat to gently undulating plains with soft, self-mulching surfaces of brown cracking clays developed from sediment from the Winton Formation (Wilson et al., 1990). Erosion of the previous land surface has resulted in variable stone cover. High available soil-water capacities and adequate nutrient levels make these soils highly productive when sufficient rainfall is received. Droughts, however, can be particularly severe, dramatically reducing vegetation cover to very low levels and making the soil vulnerable to wind erosion.

Among the most distinctive landforms of the Channel Country are the dissected remains of the Tertiary land surfaces. These vary from resistant silcrete, calcrite or ferricrete-capped tablelands, mesas and buttes, rising from 30 to 100 m above the plains, through to the undulating gibber plains (State Public Relations Bureau, 1977). These flat, detrital plains were left after the original tertiary land surfaces lowered, producing large areas of glistening red rocks.

### 2.4 Soils

The various soil types distributed throughout the Channel Country are mainly the weathered products of Cretaceous rocks, including the Wilgunya Beds, Mackunda Beds and Winton Formations (Wilson et al., 1990). These rocks were weathered and reworked by fluvial processes to form vast tracts of vertisols including red, brown and grey clays. Red and brown clays are distributed in the upper reaches of the Channel Country where flooding is rare, although the latter may also be found in the mid reaches (Isbell and Hubble, 1983; Wilson et al., 1990). Grey clays are distributed in the more-commonly flooded mid-low reaches of the Channel Country. This soil type is particularly widespread along the plains of the Diamantina and Eyre Rivers, and the numerous interdune swales and claypans that align these rivers. The clay-rich soil groups, particularly the brown clays, tend to self-mulch following wetting and drying cycles associated with flooding or local rainfall events. Alternatively, clay surfaces may form physical crusts, promoting unfavourable conditions for vegetation growth (Whitehouse, 1947; Isbell and Hubble, 1983).
The non-clay soil groups are fall into the *aridisol* greater soil group. These include the soils of the gibber plains, *shallow red earths* and *siliceous sands*, all of which are well distributed throughout the Channel Country. Gibber plains can be found on alluvial plains or nearby duricrust surfaces. The *shallow red earths* occupy the east and central northern areas of the Channel Country. The most conspicuous soils in the region are the dunefields, originally weathered from Cretaceous and Tertiary sandstones and reworked by alluvial and aeolian processes (Wilson *et al.*, 1990). Dune crests are comprised of *siliceous sands*, and *earthy sands* toward the core, flanks and interdune corridors. Hence, the soils of the Channel Country are largely the product of the alluvial and aeolian distribution of Cretaceous and Tertiary rocks.

The claypan surface of the study area is a brown clay *vertisol* with variations in surface condition from crusted, through massive and epipedal, to self mulching. The claypan surface consists of a complex mosaic of crusts, both physical and biological, co-existing across the surface. Physical crusts vary in thickness, strength and porosity from extremely loose, aerated and fragile at one extreme, to thick, massive and hard packed at the other. Biological crusts are composed of two to three species of cyanobacteria.

### 2.4.1 Dust storms

The Simpson Desert–Channel Country region has the highest dust-storm activity in Australia (McTainsh, 1998). The Dust Storm Index (DSI) developed by McTainsh (1998) uses dust event observations made by the Bureau of Meteorology across Australia to calculate where the most dust activity occurs. The DSI for 1960 to 2004 is shown in Figure 2.2, demonstrating that the most active region is around the Simpson Desert and the lower Channel Country.
2.5 Climate

2.5.1 Rainfall, evaporation and flooding

DNP experiences a hot, arid climate. A realistic picture of seasonal rainfall patterns is hard to obtain using long-term monthly figures for arid regions due to the low average values and the high level of variability (Hall et al., 1972). DNP experiences a summer-dominant rainfall pattern (up to 75 percent of falls occur in summer) although totals are low (approximate mean of 270 mm/annum) and rainfall intermittent (Figure 2.3).
The seasonal migration southward of the Intertropical Convergence Zone (ITCZ) during summer reduces the dominance of the high-pressure circulations, allowing isolated low-pressure areas and troughs to develop. These often induce unstable, moist air and produce stormy rain. High temperatures often accompany these summer rains, producing high evaporation rates. For example, annual rainfall at DNP for the decade 1994 to 2004 ranged from 70-530 mm while evaporation rates of 2703-3842 mm per annum were experienced (Figure 2.4).

In winter, the highs lie closer to the equator at latitudes around 30 to 35 degrees south, and are found in association with cold fronts. The air circulation around the highs determines the direction and type of winds blowing into the DNP in winter. These winds are generally dry and produce only light falls of rain, if any.
River flow does not require rainfall to fall locally, therefore ‘dry floods’ are frequent. Flooding of the Diamantina River at DNP occurred 61 times during the period 1994 to 2004. Flood severity is categorised by stage height, with floods commonly referred to as being minor (< 3 m), moderate (3-4.8 m), and major (greater than 4.8 m). Floods over 0.7 m prohibit the crossing of the river by vehicles, and at over 4.8 m the outer floodplains (claypans) are inundated. Five major floods occurred throughout the study period (Figure 2.5). Major floods are important geomorphically and ecologically, as they replenish sediments and nutrients and stimulate vegetation growth on the claypans.
Figure 2.5. Flooding history of the Diamantina River at Diamantina National Park for the period of 1994–2004. A major flood occurs at stage heights of greater than 4.8 m and results in the outer flood plains (claypans) being inundated with water.

2.5.2 Temperature and radiation

Air temperatures in DNP can range from the high forties (Celsius) to below freezing. The highest temperatures are in December and January, and the lowest in June and July. Figure 2.6 indicates the variation in maxima and minima temperatures measured at a two-metre height during the period 1994 to 2004. Surface temperature of the claypans at DNP measured over 65°C during one late-spring field visit. Wills (1980) reports that heatwaves are common throughout the Channel Country in summer, and winters are mild with only a few frosts, mainly in July. The moderate to large diurnal range of temperature throughout the year is due to the area’s remoteness from moderating influences such as oceans, as well as its dry, cloudless atmosphere which favours high rates of incoming solar radiation and high rates of outgoing terrestrial radiation at night (Stanely 1976).
Figure 2.6. Monthly variation in maximum and minimum temperatures for the period of 1994–2004 at Diamantina National Park. (Source: Bureau of Meteorology, unpublished data 1994–2004)

Solar radiation at DNP is highest in summer and lowest in winter (Figure 2.7). Radiation is an important climatic attribute, as it impacts on the metabolic functioning of biological life. It is probable, therefore, that cyanobacteria growing in the soil crusts are impacted by radiation.

Figure 2.7. Monthly average global radiation levels for the period of 1994–2004 at Diamantina National Park.
2.5.3 Wind

Twice daily (0900h and 1500h), the Australian Bureau of Meteorology takes long-term wind-speed readings at two neighbouring towns—Birdsville (350 km SSW of DNP) and Boulia (190 km NW of DNP). On average, wind strength is greatest in the afternoons for all months at both sites. Spring produces the strongest winds, accompanied by a greater range of prevailing wind directions. In late winter/early spring, westerlies and south-westerlies increase in strength and frequency (Figure 2.8). The annual equatorial migration of the high-pressure systems during winter months produces these stronger winds (Figure 2.8). The cold fronts and trough lines formed in association with these air masses cross the continent at the latitudes of DNP and the Channel Country. These meteorological conditions provide three distinct wind systems which Sprigg (1980) identified as producing dust storms:

- **North-westerly winds associated with troughs precede the intense cold fronts.** These winds are continental in origin and are hot and dry. Wind speeds are sufficient to produce dust storms preceding the frontal activity.

- **Westerly and south-westerly winds associated with the cold fronts can produce wall-like sand and dust storms whipped up by the passage of the turbulent, unstable air masses associated with the fronts.** This is also a time of violent Willy willies and maritime water spouts.

- **South-easterly (at southern latitudes) through southerly to south-south-easterly (in the Simpson Desert) winds produce dust and sand storms during the approach of high-gradient anticyclonic cells (high-pressure systems).** Sprigg (1980)
2.6 Vegetation

The vegetation mosaic present in the Channel Country is an expression of the relationship between the hydrological regime (precipitation, runoff and run-on), substrate and extant biota (Olsen, 1996). Species composition varies with distance from the channels as plants are forced to be more reliant on flooding and infrequent rainfall for hydration. Outer floodplain vegetation responds to good local rains as well as flooding, while vegetation on the dunes and non-flooding regions relies entirely on rainfall to initiate and maintain growth.

The Channel Country is renowned for both the volume of growth following floods and its diversity. While many trees and woody shrubs require stable surfaces for their continued survival, herbaceous plants are in a state of dynamic equilibrium with the flooding regime (Capon, 2005). Of the 1,014 recorded species present in the Channel Country...
Country, the grass family Poaceae, with 145 species, is the largest. Of the remaining 93 recorded families, Asteraceae (daisies–114 species), Chenopodiaceae (bluebush/saltbush–105 species), and Fabaceae (legumes–65 species) are the most diverse (White, 2001).

Claypans display a dynamic floristic composition varying rapidly in both space and time in response to rainfall and flooding. The Lake Constance claypan was essentially bare from 1993–1998, with less than 5 percent vegetation cover across its 25 km² during these years. Small areas supported a variety of burrs (Sclerolaena spp.) and annual grasses such as fine leaf tussock grass (Poa sieberana) and katoora (Sporobolus actinoclados). Sandy mound deposits supported small communities of pop saltbush (Atriplex spongiosa), pigweed (Portulaca oleracea) and a variety of burrs (Sclerolaena spp.), but these were transient and highly dependent on rainfall.

Between 1999-2001, rainfall was higher than average and four large floods inundated the claypan (Figure 2.5). Floristic composition across the claypan increased dramatically with cover levels exceeding 60 percent. Over fifty species of annuals and perennials, both flowering plants and grasses, appeared on the claypan. Dominant species included: katoora (Sporobolus actinoclados); silky goodenia (Goodenia fascicularis); pigface (Portulaca oleracea); various burrs (Sclerolaena spp.); mulka grass (Eragrostis dielsii); a variety of salt bushes (Atriplex spp.); a number of the mitchell grasses (Astrebla spp.); and flinders grass (Iseilema membranaceum). This rapid colonisation of the claypan by such a variety of species suggests that soil properties, in conjunction with moisture, may inhibit vegetation growth. The occurrence of saltbushes (Atriplex spp.), Marieana sp., and grey samphire (Halosarcia halocnemoides) indicates the presence of salt in the soil profile.

Sand dunes at DNP support vegetation along their flanks, with dune crests higher than 8 m usually devoid of cover. The first colonisers of the loose sand near the summit include bristle-brush grass (Paractaenum refractum) and rattlepods, the green-flowering birdflower (Crotalaria cunninghamii), and bluebush pea (Crotalaria eremaeae). The sandhill wattle (Acacia bivenosa) is also common. Further down the flanks are shrubs such as the edible spiny saltbush (Rhagodia spp.), camelbush (Trichodesma zeylanicum), forbs such as buckbush (Salsola kali) and parakeelya (Calandrinia spp.), sandhill puncture vine (Tribulus hystrix), and bitter melon
Towards the spreading base of the dunes, a greater variety of vegetation becomes established. This includes mulga, whitewood (Atalaya hemiglauca), beefwood, corkwood (Hakea ivoryi) and, occasionally, western bloodwood (Corymbia terminalis), bauhinia (Lysiyllm carronii) and western dead finish.

Vegetation on the Downs consists chiefly of barley Mitchell grass (Astrebla pectinata), katoora (Sporobolus actinocladius), annual saltbushes, rough raspweed (Halorais heteropylla), and a wide variety of burrs (Sclerolaena spp.). Vegetation is drought-hardy except in extreme, prolonged drought conditions (multiple years).

### 2.7 Current land use

The arid climate of the Channel Country restricts land use to beef cattle grazing of native pastures (Isbell and Hubble, 1983; Wilson et al., 1990). The naturally-irrigated floodplains are the key to grazing enterprises, providing vast areas of rich, but ephemeral, native pastures. In good seasons, the floodplain land systems have an estimated carrying capacity of 2–3 beasts/km² (Ritchie, 1997). The Channel Country has been grazed for over 130 years, however only in the last 40 years have improvements to stock transport, fencing and watering points reduced the environmental pressure on the land. Land degradation is still a concern, however, and its reduction relies on well-informed decision making. All cattle were removed from DNP in July 1998, allowing the faunal and floral communities to develop in the absence of grazing pressures. Changes in vegetation abundance and composition have been noticed, and monitored, since this de-stocking.

Ongoing risks to DNP include expanding populations of feral animals and weeds, as well as pressure from human recreation as the Channel Country and its surrounding areas are being visited by increasing number of tourists each year (Ritchie, 1997). Since the creation of the DNP in 1994, visitation numbers had increased twenty fold by 2004 (Whitehead pers comm. 2004). Tourism in arid regions equates to increased use of off-road vehicles, with the resultant potential for increased land degradation. Goudie (2004) coined the term “Toyota-isation” in reference to this increased pressure on sensitive arid lands from of an ever-increasing number of four-wheel-drive vehicles (of which Toyota is a major brand). Off-road vehicle tracks across
fragile, arid soils and vegetation disrupt the ecological balance, taking decades to repair. Therefore, just as the cattle industry requires careful management to ensure minimal damage to the land, conservation managers will need to plan for the integrated and ecologically-sustainable development of tourism.

### 2.8 Study sites

Experimental research was principally conducted on a large and sparsely-vegetated claypan situated on an outer floodplain to the west of the Diamantina River (24° 46’ S, 140° 59’ E). This site, within the DNP, is 8 km north of the semi-permanent waterhole *Lake Constance*, and is referred to as the Lake Constance claypan (LC claypan). The LC claypan is approximately 25 km². It is locked in by dunes to the north and south, a large floodout region of cracking clay to the west which drains Downs country (Figure 2.9), and the Diamantina River to the east. A second claypan on the eastern side of the Diamantina River was used to make observations and experiments when flooding prohibited access to the LC claypan. The Homestead claypan (HS claypan) is 15 km east of the LC claypan, and only a 5 minute drive (or canoe paddle, depending on the flood height) from the research base (Figure 2.1). A transect between the LC claypan and the HS claypan was established to determine the effect of sediment deposition into the channels of the Diamantina River. This transect, referred to here as the Boeing Transect, follows the 737 meridian across the Diamantina River (Figure 2.1).
2.8.1 Surface types of the Lake Constance claypan

The surface of the claypan is comprised of a mixture of different crust forms, sediment deposits and gravel surfaces. Crusts are the dominant surface type and are either physical or biological in origin, with both types exhibiting enormous morphological variation spatially. Physical crusts are formed through disturbance, re-sorting and relocation of sediments, primarily through the action of water. Common forms found on the LC claypan include sealed clay, clay curls, wind-sheeted, polygon cracking clay, and still depositional crusts (Figure 2.10; see Chapter 5 for a comprehensive review of claypan surface features). Biological crusts on the claypan are dominated by cyanobacteria that form thin, fibrous surface layers up to 4 mm thick.

Fine alluvial deposits occur frequently on the claypan. This alluvial sediment is initially deposited with flood events and then redistributed with wind events. Accumulations of alluvial sediment across the claypan form either small, hummocky dunes (nebkha) covering areas of up to 100 m$^2$, or sand sheets which cover tens of
square metres. Fine sand is frequently deposited behind rocks and plants, forming small, transient accumulations.

Gravel surfaces, known as *gibber*, occur across the claypan, encompassing areas tens of square meters in extent. These gibber surfaces function both as deposition zones and source areas for the fine sands.

Figure 2.10. Various soil surface types found on LC claypan. a) cyanobacteria crust on claypan; b) fractured cyanobacteria crust on dune flank—note the filaments dangling beneath crust; c) patchy gibber surface; d) sealed clay–structural crust; e) polygon sealed clay; f) an example of the patchiness in surface types across the LC claypan.
2.8.2 Field sites selected for this study

To characterise the entire diversity of surface features on the LC pan would be an enormous task and is beyond the scope of this study. Therefore, four field sites representing common surface types were selected for high-resolution investigation:

- Three sites on the LC claypan:
  - biological soil crust (denoted as “Sand Sheet”)
  - deposition physical crust (denoted as “Washout”); and
  - structural physical crust (denoted as “Sealed Clay”).

- A dune site with a well-developed biological soil crust (denoted as “Dune”).

The dune was an important addition, as it was considered a major sediment source for the claypan and it had the most developed biological crust in the environs.

2.9 Summary

The study area determined not only the scene for the research, but also the environmental influences directly contributing to the erodibility of the claypan.

The site’s geological history has had two effects:

- It has produced soils which are erodible.
- It has produced a landscape shape that transports soils from higher, humid regions to the arid centre, ensuring a continuous supply of fresh sediment to the claypan and sustaining sediment supply for wind erosion.

Climatic factors, such as temperature, rainfall and solar radiation, are pivotal in producing the diversity of surface features, such as crusts, across the claypan. It could be hypothesised that this diversity of crusts is a function of the climatic extremes which the claypan experiences, and that these extremes therefore have a significant impact on the formation and longevity of the crusts, ultimately controlling the erodibility of the soil surface from wind. Chapter 7 will investigate the specific role that three environmental factors have on the biological activity of cyanobacteria crusts, and their resultant impact on erodibility. The following chapter investigates the suite of methodologies used to answer the research questions.
Chapter 3. Field and Laboratory Methods

3.1 Introduction

Monitoring wind erosion in Australia presents a number of practical challenges:

- Locations where wind erosion is prevalent are remote. Difficulties arise in accessing sites and transporting sufficient equipment for adequate, large-scale monitoring.
- The episodic nature of wind erosion means that either:
  - personnel must be present for extended periods of time; or
  - the technology used must be able to monitor events, unchecked, for extended periods of time.
- The surface types which control soil erodibility vary greatly through time and space. Soil deposits and surface crusting vary frequently, sometimes even daily if climatic conditions (such as rainfall) are conducive.

With such a diverse set of variables controlling wind erosion, any project which sets out to characterise the erodibility of a dust source area must be equipped with an equally diverse range of sampling strategies. As this thesis takes a top down approach by starting with erodibility at the landscape scale (25 km$^2$), followed by the erodibility of different surface forms (1 m$^2$), and finally focussing on the physiology of one type of crust (0.01 m$^2$), it was critical that a wide range of measurement strategies were used. Each of these scales, in fact, required its own suite of measurement strategies. To assemble these suites and meet the aims of the study, considerable expert knowledge was drawn from the extant literature and novel adaptations were made.

3.2 Methods of wind-erosion study

While some wind-erosion studies continue to use field measurements, most projects use one of three alternative approaches:

- Wind tunnel simulations
- Modelling of dust emissions
- Remote sensing
Wind tunnels provide a uniform horizontal wind flow across a desired surface, guaranteeing the required research result without needing to wait for appropriate natural winds of a suitable speed. Portable field wind tunnels vary in size from smaller tunnels 3 m long (Belnap and Gillette, 1998) to large, trailer-mounted tunnels 12-16 m long (Leys and Raupach, 1991; Maurer et al., 2006).

Numerical models and remote sensing have increased in popularity, largely due to a perceived reduction in costs and time when compared to field-based research. Models such as Wind Erosion Prediction Scheme (WEPS) (Hagen, 1991) and Wind Erosion Assessment Model (WEAM) (Lu and Shao, 2001) use atmospheric, vegetation and soil characteristics to predict erosion from the paddock to the continental scale. Models such as these have highlighted the need to incorporate more information on the spatial and temporal variation of soil-surface conditions (Marticorena and Bergametti, 1995; Böhner et al., 2003; Zender et al., 2003). Chappell et al., (2005; 2006) have proposed that the most efficient, non-intrusive way to assess soil surface condition is through remote sensing. Using either small land-based platforms or satellite platforms, remote sensing has proved that it is able to distinguish cover levels of vegetation (Williamson and Eldridge, 1993), varying soil conditions (Chappell et al., 2003ab), and even biological crust presence (Karnieli et al., 1996; Karnieli et al., 1999).

Traditional instrumented field studies have not been completely replaced by these methods. Instrumented sites monitoring natural rates of wind erosion still provide valuable process information. A long-term study by McTainsh et al., (1999) using simple, passive sediment traps was able to identify the importance of rainfall and flooding on the rates of wind erosion in the Channel Country. Hupy (2004) and Reheis (2006), using similar traps, were able to demonstrate both the spatial and temporal variation of wind erosion.

A combination of methods is required to piece together the intricate processes controlling wind erosion, particularly when attempting to report at large scales such as continental scales. Underlying these large scale processes however is a number interacting small scale processes. Therefore to understand wind erosion at a
continental scale requires understanding and measurement of the small-scale processes which control soil-surface erodibility.

Erodibility measures have traditionally concentrated on a few parameters (such as soil texture, aggregation levels, organic content and soil moisture) which are then related to wind erosion (Leys et al., 1996; Leys and McTainsh, 1996). This thesis acknowledges that soil erodibility is a composite of many interacting parameters. Therefore, in order to achieve a more holistic view of erodibility, I have incorporated a diverse range of methodologies characterising the response of crusts to a range of either simulated or natural environmental conditions.

This chapter describes the suite of methodologies used to address the objectives of the study. They can be divided into the four main objectives (Figure 3.1) as follows:

1. Methods used to characterise the soil surface of the Lake Constance claypan at a landscape level
2. Methods used to determine the erodibility of four key soil surface types from the Lake Constance claypan
3. Techniques required to profile the ecophysiology of cyanobacterial crusts
4. Methods used to quantify the entrainment of wind-eroded sediment and cyanobacteria
3.3 Characterising the soil surface of a claypan

- Broad scale mapping of geomorphic regions
- High resolution mapping of surface type

3.4 Determining the erodibility of soil surface types

- Modelled sediment flux
- Particle-size and population characterisation
- Sediment flux from different soil surface types
- Soil crust strength
- Spatial patterns of surfaces

3.5 Ecophysiology of cyanobacteria crust

- Photosynthetic response
- Polysaccharide content
- Organic carbon content
- Chlorophyll content
- Taxonomy

3.6 Entrainment

- Sediment traps
- Characterisation of entrained sediment

Figure 3.1. This thesis uses a variety of methods in order to characterise the erodibility of LC claypan. These methods can be grouped into four functional suites which align with the research aims.

### 3.3 Characterising the soil surface of a claypan

The methods used to characterise the soil surface relate directly to the first aim of this study: to investigate types and spatial distributions of soil surfaces across a claypan of the outer floodplain of the Diamantina River. The approach taken typifies field assessment of a site’s vulnerability to wind-erosion. First, the surfaces were classified into broad geomorphic regions based on a quick, visual assessment. Then, as knowledge of the field site increased (through measurements, for instance), the scale of the study was reduced. This top-down approach forms this chapter and in effect the thesis.
3.3.1 Broad scale mapping of geomorphic regions

In 2000, the claypan surface was surveyed for four geomorphic regions by driving NE–SW transects across the claypan with a quad motorcycle. Thirty-three transects spaced 150 m apart were driven. While traversing, GPS and odometer readings were taken at each change in surface class. The surface groupings had relevance to wind erodibility and could be characterised into:

- cracking clays
- sealed clays
- gibber; and
- streamlines.

The percent cover of each surface class was calculated for each transect and a final approximation of claypan coverage was estimated by pooling the transect values. The results of this technique will be used in Chapter 5 to provide a broad-scale assessment of areas on the claypan that are potentially erodible.

3.3.2 High resolution mapping of surface type

Also in 2000, high resolution sampling of sediment flux, sediment characteristics and vegetation, along with mapping of surface type, occurred at 157 sites across the claypan. The sample locations were randomly selected and conform to the geo-statistical layout as outlined in Chappell et al., (2003a). In brief, six transects across the claypan were created, forming the sides and diagonals of a parallelogram. Along each of these main transects, ‘nodes’ were located at 500 m intervals. There were 40 nodes in total across the study area. A smaller transect, known as the nest, radiated from each node for 1000 m in a direction randomly assigned along compass bearings. Three potential sampler locations were positioned along each of these nest transects at 200, 500 and 1000 m. In total, there were 160 possible sites for trap placement. Due to flooding, however, 3 sites were not accessible during the field season.

Sediment flux

Forty passive wind-vane sampler traps (Fryrear, 1986) were randomly assigned among the 157 possible sites. The restriction of trap numbers meant that only one trap was allocated to each node and its related nest. Sediment was collected after each wind event and traps relocated to 40 new randomly-chosen positions.
Surface characterisation

Soil characteristics were laboratory analysed to assess the pre-existing soil conditions that may contribute to the formation and distribution of crusts. These analyses included:

- **Coarse resolution particle-sizing.** Samples were analysed at a coarse level for particle-size groups: clay <2 µm; silt 2–20 µm; fine sand 20–60 µm; and coarse sand >60 µm
- **Electrical conductivity** of each sample, determined using the 1:5 method as outlined in Rayment and Higginson (1992)
- **Percentage vegetation and gibber cover,** estimated using a 0.5 m² quadrat
- **The dominant surface type,** visually assessed at each of the 157 sites. Physical crusts were described according to the work of Valentin (1986), while the biological crust nomenclature referenced three different classification schemes:
  - Eldridge and Greene (1994) who classified Australian biological soil crusts according to functional field diagnostic traits
  - Belnap and Lange (2003) whose scheme has four classes based on morphology at a global scale; and
  - A scheme presented by Thomas and Dougill (2006) which looked solely at cyanobacteria crusts.

Due to the differences in names outlined in these three classification schemes, biological crusts in this thesis will be called cyanobacteria crusts, as these are the organisms that dominate the biological crusts on site.

The results from this section are used in Chapter 5 to identify the spatial distribution of different surface types and their relationship, if any, to sediment flux or soil characteristics.

### 3.4 Determining the erodibility of soil-surface types

The following methods were used to meet this study’s third objective: to determine the erodibility of different soil-surface types found across a claypan of the outer floodplain of the Diamantina River. Initially, erodibility was estimated using models
for the four field sites. A range of measurements was then taken to characterise the erodibility of crusts on the claypan, with each measurement targeting a slightly different aspect of erodibility. Measurements included:

- sediment removal under different wind speeds
- the effect of saltation impact
- surface strength; and
- percentage cover.

This multi-measurement approach is aimed at producing a more holistic characterisation of the soil-surface erodibility. Erodibility studies usually only measure a couple of parameters, incorporating the results into empirical formulas. In order to fulfil this study’s third objective, however, a specialised instrument was developed: the micro wind tunnel. The development of this instrument satisfies the second aim of this thesis: to develop an appropriate methodology for measuring the wind erodibility of small patches of variable soil surfaces. The micro wind tunnel is not only an important methodology, but is also an important development in terms of instrumentation. For this reason, Chapter 4 will discuss the development and testing of the micro wind tunnel in detail.

### 3.4.1 Modelled sediment flux

The Wind Erosion Assessment Model (WEAM: Shao et al., 1996) was used to predict the sediment flux from four field sites (dune, sand sheet, washout and sealed clay, as described in section 2.8.2). The model was used in Chapter 6 to provide a starting point for exploring erodibility. Specific details of the model and its use in this thesis can be found in Chapter 6.

### 3.4.2 Particle-size analysis

Particle-size analyses were conducted on a number of crusts and trapped transported sediments. Particle-size distributions of crusts and sediments collected either in traps or with the MWT were determined using the Multisizer 3 (Beckman Coulter), a high-resolution particle-sizing instrument which uses an electrical sensing zone as a means of counting the number and size of particles suspended in an electrically conductive liquid (Lines, 1992). As the Multisizer requires an electrolyte, the samples are technically subjected to some disaggregation while in suspension. However, as
McTainsh et al., (1997) propose, any aggregates that survive this electrolyte treatment would be stable enough to survive the rigours of sediment transportation, therefore it is accepted that any aggregation during minimally-dispersed analyses would be transport stable. The analytical range of the Multisizer is 1.4–600 µm.

3.4.3 Particle-size population analysis

Population analysis was used to characterise the populations within the particle-size distributions. Geomorphic processes and parental sediment sources can produce unique particle-size populations. A particle-size distribution usually consists of a number of populations, and in the LC claypan, floods, rain and wind have ensured that multiple populations do exist.

MIX 3.1 is a population-fitting software package developed for population ecology (Macdonald and Greene, 1988). It has successfully been used to identify populations within sediment particle-size data (Leys et al., 2005; Livingstone et al., 2006). Data was processed using the Quasi-Newton algorithm and none of the parameters were fixed, allowing the model to determine the populations, proportions and their variances.

3.4.4 Sediment flux from different soil surface types

Wind tunnel technology was employed to determine the sediment flux from four field sites (dune, sand sheet, washout and sealed clay, as described in section 2.8.2). The difference in fluxes allows relative erodibility to be determined. Adding saltation material simulates saltation bombardment, determining the surface’s resistance to saltation abrasion.

A micro wind tunnel (MWT) was developed to specifically analyse erodibility at small scales. This was necessary to determine erodibility of the highly variable soil surfaces, in particular crusts. The tunnel had to be small enough to test discrete crust surfaces without encroaching on multiple types. The distribution of different crust types (whether physical or biological) can vary within a metre, so traditional larger field wind tunnels (up to 12 m length) would be testing an area that encompassed a number of different crust types, micro-morphological features and vegetation. Its small size also allowed the tunnel to be operated by one person and to be portable enough to use in locations usually difficult to access (e.g. dune crests). Development
of the MWT required considerable calibration and testing of its performance. The specifications and results of those tests are given in Chapter 4.

3.4.5 Soil crust strength

Soil crust strength is thought to provide a reliable measure of resistance to surface abrasion. Using a GeoTechnic pocket penetrometer (Figure 3.2) with a tip diameter of 6 mm, the crust strength was tested in situ. Three hundred randomly-allocated measures were made on each of the four field sites (dune, sand sheet, washout and sealed clay). Units of crust strength are expressed in kg cm$^{-2}$.

Tests of crust strength are rapid and easy to make with the type of penetrometer used. The hand-held nature of the penetrometer, however, creates the potential to alter the main axis of pressure, preferentially compromising the crust. Many laboratory-based penetrometers avoid this problem by balancing crust pieces over a balance beam while a stepping motor gradually increases the pressure (McKenna Neuman et al., 1996; Rice and McEwan, 2001). The best tip diameter to use has been discussed in the literature, with the general consensus being that the smaller the better, as this most effectively simulates the impact energies of saltation particles (Rice, 1997). Although use of penetrometers in the field is reported (e.g. Houser and Nickling, 2001; Thomas and Dougill, 2007), the type used is often not clearly described.
Figure 3.2. The GeoTechnic pocket penetrometer in use testing the crust strength of a physical crust.

3.4.6 Spatial patterns of surfaces
Spatial patterning may increase variation in erodibility of a site. For example, fine cracking of the soil surface provides preferential fracture sites, thereby reducing the erodibility of the site. Each time the micro wind tunnel was used at one of the four field sites, a one metre line transect was conducted characterising three basic surface types and features at 100 mm intervals. Noted were:

- **structural** (a physical crust)
- **crack** (a fracture in the soil surface up to 2 mm in width); and
- **cyanobacteria** (biological crust containing cyanobacterial filaments).

The combined transects were used to assess the spatial heterogeneity at each crusted surface by expressing the surface features as a percentage of cover.

3.5 **Ecophysiology of cyanobacteria crusts**
The methods used to determine the physiology of cyanobacteria relate directly to the fourth aim of the thesis, namely, to improve understanding of cyanobacterial response
to three environmental factors: hydration (i.e. rainfall), light (i.e. solar radiation) and
nutrients. A range of experiments was conducted, both in the field and in the
laboratory, to gain insight into how these organisms respond to the environmental
factors. This baseline information was needed in order to understand how these
‘living’ crusts function in the claypan environment, and in turn impact on the
erodibility of the claypan.

Testing the environmental parameters requires at least one measure which
discriminates between the effects of the applied treatment, regardless of whether the
treatment is hydration, light or nutrients. Various measures have been used in the
literature:

- Monitoring of real time physiological responses, such as respiration production
  rates (measured with CO₂ and O₂ monitoring instruments) and photosynthetic
  activity (measured with fluorometers)
- Analytically quantifying the amounts of metabolic products, such as chlorophyll a,
  polysaccharide secretions, and total organic carbon
- Quantifying biomass by conducting cell counts with either standard or epi-
  flourescent microscopy
- Surrogate measures of surface activity using a range of remote-sensing platforms,
  from land based radiometers to satellites

Using any of these measures is difficult because of two issues which commonly
occur. First, there is an enormous diversity in instrumentation and analytical
procedures which results in no standard method to measure the effect of
environmental factors. An example of this can be seen in the multiple ways that
polysaccharide content has been measured. Literature reports differences in analytical
technique, the type of extractants used, and the extractant conditions required (Dubois
et al., 1956; Molope et al., 1987; Malam Issa et al., 2001).

The second difficulty relates to the diversity of organisms within the biological soil
crusts. Their morphology, physiology and temporal behaviour vary so greatly that no
single measure would adequately describe all of them, therefore necessitating a
variety of measures. This becomes a problem because careful descriptions are
required not only of the measures being used, but also the type of organisms they are being used on.

Throughout this thesis I will present data from the literature that describes higher-order BSC organisms (lichens and mosses) to identify trends and ranges of response. As the BSC on LC claypan are dominated by cyanobacteria crusts, I will attempt to draw on as much of the specific international literature as possible.

### 3.5.1 Developing a suite of measures

The diversity of measurement techniques available and the often-limited reporting of analytical details by other studies meant that a number of measures were trialled in this thesis. The techniques that were found to provide the most reliable results were chosen to characterise the ecophysiology of the cyanobacteria crusts and are shown in Table 3.1. The selection of these techniques is the outcome of much work, with quite a number of common measurement techniques not being used. For more information regarding these techniques refer to Appendix A. Fine-detail experimental design information is given in Chapter 7 before each experiment description.
Table 3.1 The range of experiments and measurement techniques used to determine the ecophysiology of cyanobacteria crusts.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Measurement technique</th>
<th>Instrument/methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydration: Preliminary</td>
<td>Real time physiological responses</td>
<td>Mini-PAM</td>
</tr>
<tr>
<td>Hydration: Lab #1</td>
<td>Real time physiological responses</td>
<td>Mini-PAM</td>
</tr>
<tr>
<td></td>
<td>Metabolic products</td>
<td></td>
</tr>
<tr>
<td>Metabolic products</td>
<td>Chlorophyll a</td>
<td></td>
</tr>
<tr>
<td>Light: Preliminary</td>
<td>Real time physiological responses</td>
<td>Mini-PAM</td>
</tr>
<tr>
<td>Light: Pre dawn survey #2</td>
<td>Real time physiological responses</td>
<td>Mini-PAM</td>
</tr>
<tr>
<td>Nutrient: Lab #3</td>
<td>Metabolic products</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chlorophyll a</td>
<td></td>
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<tr>
<td></td>
<td>Polysaccharide</td>
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<tr>
<td></td>
<td>Organic carbon</td>
<td></td>
</tr>
<tr>
<td>Nutrient: Lab #4</td>
<td>Real time physiological responses</td>
<td>Phyto-PAM</td>
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<tr>
<td></td>
<td>Metabolic products</td>
<td></td>
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<tr>
<td></td>
<td>Chlorophyll a</td>
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<td></td>
<td>Polysaccharide</td>
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<td></td>
<td>Organic carbon</td>
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<tr>
<td>Characterising cyanobacteria in entrained sediments (Chapter 8)</td>
<td>Biomass</td>
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<td></td>
<td>Metabolic products</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chlorophyll a</td>
<td></td>
</tr>
</tbody>
</table>

3.5.2 Real time physiological responses

Photosynthetic monitoring

Chlorophyll fluorescence was used to identify when the photosynthetic apparatus of the cyanobacteria was operating. During desiccation, no photosynthetic activity occurs and hydration is required to activate it (Rascher et al., 2003). Fluorometers allow non-invasive, near-instantaneous measurement of key aspects of photosynthetic light capture and electron transport. While these techniques were originally developed to investigate the fluorescence signals of vascular plants, during the life of this study specific fluorometers were developed for use with phytoplankton and photobionts. Fluorometers had been used on cyanobacterial photobionts (lichens), algae, epilithical cyanobacteria and snow covered lichens before (Pannewitz et. al., 2003), however the appropriateness of using the technology on arid soil crusts remained
untested. Two types of fluorometers were used in both the field and laboratory to determine:

- the appropriate hydration regime
- whether the technology could be usefully applied to arid soil cyanobacteria crusts; and
- whether the addition of nutrients stimulated photosynthetic activity and therefore growth.

**Mini-PAM**

A miniaturized pulse-amplitude modulated photosyntheses yield analyser (Mini-PAM, Walz, Effeltrich, Germany) was used to investigate the effect of hydration and light on cyanobacteria crusts. Organism response to the environmental treatments was measured by monitoring the changes in chlorophyll $a$ fluorescence.

Three different hydration rates were tested in the laboratory. Small pieces of crusts (~200 mm$^2$) were carefully positioned in the Mini-PAM leaf clip to allow distance between sample and signal beam to be kept consistent. Pre-determined quantities of water for each crust sample (see Chapter 7) were added with a micro-pipette. Potential quantum yield of photosystem II (PSII), $F_v/F_m$, was measured where $F_v$ is maximum variable fluorescence ($F_v = F_m - F_o$), $F_m$ is maximum fluorescence of the dark-adapted crust during a saturation light flash (800 ms, 3000 µmol m$^{-2}$ s$^{-1}$), and $F_o$ is ground fluorescence of the dark-adapted organisms. The apparent effective quantum yield of PSII ($\Delta F/F_{m}'$) of light-adapted crusts was calculated as $(F_{m}' - F)/F_{m}'$, where $F$ is fluorescence of light-adapted samples and $F_{m}'$ is the maximum light-adapted fluorescence when a saturating light pulse, as described above, is superimposed on the prevailing environmental light conditions (Schreiber *et al.*, 1995). The individual measurements, $F_{m}'$, $F$, $F_m$ and $F_o$, were all used as diagnostic features of the crusts’ response to hydration. Electron transport rates (ETR) are not reported here as the accuracy of the light reflection factor for cyanobacteria may be unreliable (Schreiber *et al.*, 2002).

The effects of light were tested in the field using the same Mini-PAM. The operating specifications used in the field were the same as those described above for the hydration experiment in the laboratory. Field samples, however, remained part of the
soil surface and were not removed as crust pieces, therefore they were not placed in the Mini-PAM leaf clip. In order to use the Mini-PAM in the field, a special holder of a similar design to that used by Rascher et al., (2003) was placed on the soil surface. This held the fibre-optics at an angle of 60° and at a constant distance of 8 mm from the crust. The secondary NiCr/Ni thermocouple of the IAQ-CALC was placed on the soil surface near the measuring spot to record surface temperature. Irradiance (400 – 700 nm) was measured using the micro-quantum sensor of the Mini-PAM leaf clip.

**Phyto-PAM**

A PHYTO-PAM chlorophyll fluorometer (Walz, Effeltrich, Germany) was used to investigate the effect of nutrients on cyanobacteria crusts. Organism response to the addition of different nutrients was measured by monitoring the changes in chlorophyll $a$ fluorescence in laboratory samples.

The PHYTO-PAM is equipped with a special emitter-detector unit (PHYTO-EDF) designed for investigating microphytobenthos, periphyton, and microbial mats. The PHYTO-EDF features fiberoptics connected to various measuring and actinic light-emitting diode (LED) light sources via miniature fibre couplers to a photomultiplier detector. A compact emitter-detector box houses four different LED measuring light sources (470, 520, 645 and 665 nm), four LED actinic light sources (655 nm) and a photomultiplier detector. A single 1.5 mm plastic fibre carried the fluorescence signal to the detector, which was protected by a long-pass filter ($\lambda > 700$ nm). The fibre optics combined at a 4 mm active diameter at their end. A perspex rod 4 mm in diameter was used to mix the different types of light and guide the fluorescence to the detector fibre. During analyses, the end of the rod made contact with the crust samples. A dark box, covering the sample and the fibre-optic end piece, was used to prevent ambient light from reaching the sample.

The PHYTO-PAM was operated in conjunction with a laptop running the PhytoWin data-acquisition software (Heinz Walz GmbH). The key strength of this instrument is the software which deconvolutes the fluorescence responses of the major algal groups. Reference spectra can be programmed into the instrument enabling the user to increase the refinement between major algal groups. Future investigation into
monocultures of ‘within’ groups (i.e. difference signal between cyanobacteria) would be an interesting development of this technology.

The PHYTO-PAM continuously monitored the chlorophyll fluorescence yield (F) using four different excitation wavelengths simultaneously: \( F_{470} \); \( F_{525} \); \( F_{640} \); and \( F_{665} \). Actinic illumination was applied, amounting to 120 µmol quanta m\(^2\) s\(^{-1}\) of 660 nm light. This did not lead to any photoinhibition considering that full \textit{in situ} irradiances of BSC commonly reach over 2,500 µmol photons m\(^2\) s\(^{-1}\). The potential quantum yield of photosystem II (PSII), \( F_v/F_m \), was measured by applying a saturation pulse.

Saturation pulses were applied with the actinic light LEDs (660 nm) at an intensity of approximately 1,800 µmol quanta m\(^2\) s\(^{-1}\) of 660 nm.

3.5.3 Metabolic products

Polysaccharide determination

Soil cyanobacteria excrete polysaccharides to form protective layers against harsh environmental conditions. Therefore quantification of polysaccharide content occurred to determine the presence of cyanobacteria in different soil crusts and measure metabolic growth after laboratory experimentation.

Neither the soil literature nor the BSC literature contains a single consistent method for determining polysaccharide content. There are three areas in which methods vary:

- the analytical technique used
- the extractant used; and
- the conditions under which the chemical extraction occurred.

The preferred analytical technique appears to be the phenol-sulphric method, however the extraction techniques vary between using sulphuric acid (at various molarities)(Conteh \textit{et al.}, 1998; Mazor \textit{et al.}, 1996), phenol (Veiga \textit{et al.}, 1997) and sodium chloride (Underwood \textit{et al.}, 1995). Within each of these, the extraction conditions also varied, from one hour in concentrated H\(_2\)SO\(_4\) to 24 hours at 80°C in 1.5M H\(_2\)SO\(_4\). The anthrone technique displayed similar inconsistencies (Metting and Rayburn, 1983; Molope \textit{et al.}, 1987; Rogers & Burns, 1994; Degens and Sparling, 1996).
Two studies specifically analysed the polysaccharide content of BSC largely comprised of cyanobacteria: Mazor et al., (1996); and Malam Issa et al., (2001). The analytical techniques differed between them with the former using the phenol-sulphuric acid technique and extracting in concentrated H$_2$SO$_4$, while the latter extracted with 0.6M H$_2$SO$_4$ and analysed with gas chromatography.

For this thesis, polysaccharide content in crust samples was determined using the phenol-sulphric acid technique of Chaplin and Kennedy (1986) with the extraction technique of Lowe (1993). Polysaccharides were extracted from 1.5 g of soil with 100 ml of 0.5M H$_2$SO$_4$ autoclaved at 100 °C at 101 kPa pressure for one hour (Lowe 1993). Content was determined by adding 1 ml of the extracted solution to 1 ml of 5 %w/vol phenol solution. Five millilitres of concentrated H$_2$SO$_4$ was pipette pumped into this mix and allowed to sit for ten minutes. Samples were shaken, rested for 30 minutes and then shaken again. Each sample was analysed with a Shizadu UV/VIS spectrophotometer at a wavelength of 490 nm using a spectrophotometer cuvette with a beam length of 1cm. Polysaccharide content was determined by comparison to a set of glucose standards that were made on the day of analysis. Six standard concentrations were used: 50, 100, 150, 200, 250, and 300 parts per million (ppm). Polysaccharide content was expressed as ppm.

**Organic carbon content**

Organic carbon content was measured as part of the nutrient experiment. All biological life contains carbon, a by-product of metabolic activity. Increases in organic carbon content were expected in those samples with optimal nutrient levels for growth. Organic carbon content was determined with the Loss on Ignition techniques as outlined by Boon et al., (1998). Combustion temperature was 375 °C for four hours ensuring that only organic carbon and not inorganic carbon was combusted.

**Chlorophyll a analysis**

As cyanobacteria are photosynthetic organisms, they contain chlorophyll $a$ and $b$. Chlorophyll $a$ was quantified in soil crusts and laboratory experiments to indicate cyanobacterial presence and the level of metabolic production which had occurred.
Although chlorophyll measurement is a common activity, no single, consistent method is described in either the soil or BSC literature (Lorenzen, 1967; Belnap et al., 1994; Howard and Warren, 1998; Budel, 1999). After trialling a number of techniques, the Ronen and Galun (1984) method was found to provide consistent results and this method is described below.

Chlorophyll \(a\) was extracted from 1.5 g samples of soil with dimethyl sulfoxide (DMSO) (Ronen and Galun 1984) as follows:

1. Ten millimetres of DMSO was added to each 1.5 g soil sample and the samples were shaken for 5 minutes.
2. The samples were given two cycles of heating at 65 °C for 30 minutes, with 5 minutes of shaking between each cycle.
3. The samples were then allowed to cool down in the dark.
4. Each sample was then centrifuged at 2,500 rpm for 10 minutes.
5. Following centrifuge, each sample was analysed using a Shizadu UV/VIS spectrophotometer at wavelengths of both 665 nm and 730 nm. Using a spectrophotometer cuvette with beam length of 1 cm, values for the absorbance peak of chlorophyll \(a\) and the correction factor for turbidity were determined.
6. After recording the absorbance values at both peaks, the samples were acidified with 20 \(\mu\)L of HCL for 5 minutes, and mixed thoroughly. Absorbance values were then recorded again at both peaks.
7. The micrograms (\(\mu\)g) of chlorophyll \(a\) per cubic centimetre of soil was calculated using equation 3.1 (Howard and Warren, 1998).

\[
\text{Chlorophyll } a = 89.3[(665_{\text{before}} - 730_{\text{before}}) - (665_{\text{after}} - 730_{\text{after}})] \quad [3.1]
\]

This equation assumes a sample of 1.5 g of dry soil and a spectrophotometer cuvette with a beam length of 1 cm.

**3.5.4 Biomass**

Epifluorescence microscopy was used to identify the presence and biomass of cyanobacteria in the transported sediment samples. This process is applicable to section 3.6.2 and a full description of methods will be given below. Epifluorescence
microscopy is mentioned here for completeness of the description of measurement techniques used.

### 3.5.5 Taxonomic assessment

Light microscopy of unstained specimens (200x magnification) was used to identify cyanobacteria organisms to the genus level for all samples of interest. The standard taxonomic guides, Desikachary (1959) and Anagnostidis and Komarek (1988), classify organisms on their morphological characteristics. Unfortunately, the order of Oscillatoriales, to which many desert species belong, is in a state of taxonomic confusion. The traditional morphological classifications have been challenged by recent studies using 16S rDNA sequencing. The results of these molecular methods suggest some species currently assigned to different genera are more closely related than some within-genus species. Particularly problematic is the genus *Microcoleus* that appears to be polyphyletic in nature and may be split into several genera in the future (Belnap *et al.*, 2003). As this taxonomic confusion remains unresolved, this thesis uses traditional morphology-based classifications.

### 3.6 Entrainment of wind-eroded sediment and cyanobacteria

The methods used to characterise the entrainment of wind eroded sediment and cyanobacteria relate directly to the fifth aim of this thesis: to investigate the likelihood of cyanobacterial crust propagules being entrained by the wind. Sediment entrainment is well studied, but the entrainment of biological material with it is not. Cyanobacterial crusts are conspicuous occupants of the LC claypan, so it would seem reasonable that they too are relocated by wind around the landscape. Techniques used to sample sediment entrainment and within-claypan transport provide the opportunity to investigate the movement of cyanobacteria.

To investigate the likelihood of cyanobacterial crust propagules being entrained by wind, a series of samples was collected to detect entrainment, transportation and deposition of sediment. These samples were analysed for mineral and biological properties to determine the nature of the entrained material and the presence of biological propagules.

The sampling strategy therefore included two elements:
• collection of both transported and deposited sediment; and
• analysis of the characteristics of the collected sediment samples

3.6.1 Sediment traps

Three types of sediment traps were used to quantify the amount of sediment movement around the LC claypan and across the Diamantina River:

• The micro wind tunnel was used to assess the potential erodibility and removal of cyanobacterial propagules.

• Wind vane samplers (WVSs) were used to characterise the saltation and suspension fraction up to 2 m above ground level (Figure 3.3a). Six WVSs were spread across the LC claypan and dune to characterize the spatial emission from the claypan (McTainsh et al., 1999).

• A semi-isokinetic Tonto tower collected suspension material at 2, 3, 5 and 10 m heights (Figure 3.3b). One tower was positioned centrally on the LC claypan to characterise the vertical distribution of sediment concentrations (Nickling et al., 1999).

The latter two trapping techniques were erected for other projects and have stayed in situ for various time periods over the previous twelve years.

Deposition traps were set up across the Diamantina River specifically for this project to measure deposition rates and characterise the biological material transported with dust (Figure 3.3c). Seven arrays of mesh deposition traps were spread across 15 km of the river:

• one on either edge of the river

• one in the middle of the river on an inter-river claypan; and

• the remaining four either side of a tree line.

Each array consisted of three PVC boxes (0.395 x 0.295 x 0.120 m) placed on 2 m high tripods spaced 5 m apart. The traps had a 1 mm screen placed 15 mm below the rim of the box to prevent re-entrainment of trapped dust (Leys and McTainsh, 1999).
Figure 3.3. Sediment traps used to quantify sediment concentrations with a) a wind vane sampler; and b) a tonto tower. Dust deposition rates were quantified using c) a mesh deposition trap.

3.6.2 Characterisation of entrained sediment

Samples intercepted by traps can provide considerable information about the eroded sediment. Particle-size and population analysis can be used to suggest both the height attained and the distances travelled. It can also be partially used to interpret the origin of the sediment. The presence of cyanobacteria in sediment samples was tested using fluorescence microscopy. The methods for particle-size and population analysis are provided in section 3.4.2.
**Epifluorescence microscopy**

Epifluorescence microscopy was used to identify the presence and biomass of cyanobacteria in the transported sediment samples. Sample sizes are frequently small, prohibiting other analytical techniques. Fluorescence microscopy uses small sample sizes and relies on visual observation to determine the presence of cyanobacteria.

Samples were collected using a variety of techniques to represent the range of aeolian processes: saltation; creep; transport; and deposition. Sample selection was opportunistic, drawing on ten years of experimentation at LC claypan. Samples were either washed from the collection filters as per Kiefert et al., (1992) or removed from the sampling vials dependent on collection technique.

From each sample, one gram of sediment was diluted to 1:100 with deionised water for microscopy. The nucleonic stain Acridine Orange was used to stain the genetic material of the cells. Although cyanobacteria are auto-fluorescing, the stain helped greatly in positively identifying the organisms, as focussing was often difficult due to the size of the organisms and the associated change in depth of field. Stained suspensions were passed through a 20 mm diameter 0.45 µm Millipore Nitrocellulose filter paper and oil mounted on a glass slide. Cell counts were made by viewing fluorescing cells at 1000x magnification under short-wave UV light filtered from a mercury lamp using a dark field and green excitation filter (cyano–phycocyanino) (Lepossa, 2003; Griffin et al., 2001). Autofluorescence of the cyanobacteria under red light was used to confirm identification of the organisms. Twenty frames of view were captured using the IM50 video capture program, allowing cell counting post the microscope session. Density of cyanobacteria propagules is expressed as cells/g of sediment.

### 3.7 Statistical methods

All statistical analyses were undertaken on unmodified data, that is, no transformations were made. It was assumed that all measurements made were independent of each other and that the underlying population from which the sample measurements were drawn were normal. Simple histograms were used to determine if the distributions looked normal or skewed. Statistical analyses which were used included; t tests, one way ANOVAs, simple linear regressions, test for parallelism and
coincidence of regression slopes. These analyses were conducted using version 9 of the SAS statistical analysis package (SAS, 1995). MIX 3.1 a statistical curve fitting program was used to quantify the proportion of modes in the particle-size distributions presented in chapter 6. Full description of this statistical package can be found in chapter six.

3.8 Summary

This chapter has described:

• trials of a number of different methodologies
• the successful or unsuccessful outcomes of these pilot studies; and
• the basic operation of each technique and instrument.

Subsequent chapters will therefore have only a brief description of methodologies, highlighting specific information pertinent to that chapter.

The wide range of techniques used reflects both the multidisciplinary nature of the study and the absence of research pertaining to cyanobacterial crusts in Australia. Most of the field techniques used have been developed specifically for this project or adopted from other research areas. While laboratory techniques are generally standard, slight modifications were sometimes required to increase the sensitivity for working with arid crust samples. For example, a number of commonly-employed methodologies (i.e. wind tunnel simulations, soil strength testing and particle size) were used to characterise the relative erodibility and the dust emission from the soil surface. The study of cyanobacterial crusts, however, resulted in the need for specialised techniques. Monitoring the in situ ecophysiology of these crusts provided many challenges. Techniques used were adopted from other research disciplines, modified to increase sensitivity for the target organism, and modified for use in an arid environment.

As stated, a wide range of techniques was trialled, but not all proved successful. These failures or unsatisfactory results stemmed from a lack of instrumentation sensitivity, incompatibility to the ecophysiological requirements of cyanobacteria, and monitoring at inappropriate scales. These complications need to be placed within a temporal context of the international literature. Key developments in monitoring
instrumentation, such as CO2 soil chambers (Lange et al., 1997; Hoon, 2005), flurometers (Bowker et al., 2002; Rascher et al., 2003), DNA analyses (Meeks et al., 2001) and remote sensing (Karnieli et al., 1999; Karnieli, 2002), occurred during the life of this thesis. Ultimately, the suite of techniques used represents a wide range of methodologies principally drawn from two research fields in an attempt to develop an improved understanding of the impact of crusts on emission rates from soil.
Chapter 4. Micro Wind Tunnel: Development and Testing

4.1 Introduction

This chapter describes more than just another methodology; it describes the rationale, construction detail and calibration testing of a new, specifically-designed instrument for measuring wind erosion at small field scales. The micro wind tunnel was specifically designed to balance the real need for practicality in the field with a scientifically-valid wind tunnel. The small dimensions of the final prototype were aimed at allowing its use with the different surface types found at the field sites.

4.2 The use and design of wind tunnels

Wind tunnels, used to simulate air flowing over a surface, are important tools for improving the understanding of wind-erosion processes. They can provide either empirical measurements of sediment loss from a soil surface or provide the input data for numerical models. Wind tunnels are commonly used to determine the effects of agricultural activities on wind erosion, where a mechanistic, statistics-based approach is used to distinguish differences in sediment flux resulting from different soil types or agricultural treatments.

Field wind tunnels have been constructed to suit numerous purposes (see Table 4.1 for a review of these). In general, wind tunnels are constructed as large as practically possible in order to simulate the natural processes of real wind (Chepil, 1953). Maurer et al., (2006) prescribe three functional demands necessary in designing any given field wind tunnel:

- The tunnel must achieve wind speeds that reflect natural conditions.
- The tunnel must not distort the aerodynamic flows within.
- The tunnel must be easy to transport, assemble and handle.

In addition to these three basic criteria, Raupach and Leys (1990) propose that the flow in a portable wind tunnel must meet other criteria in order to model the three modes of particle movement: creep, saltation and suspension. Their criteria include the following:
• Air flow within the tunnel must reproduce a natural-logarithmic wind profile to ensure realistic aerodynamic forces on saltating grains in flight.

• Surface shear stress must scale correctly with wind speed to ensure that realistic aerodynamic forces act on all grain sizes.

• Vertical turbulence intensity and scale close to the ground must be close to reality.

• Air flow within the tunnel must be spatially uniform, avoiding scouring by unusual jet streams.

• Large scale turbulences (gusts) should be generated in tunnel air flow, as erosion is often initiated by these higher surface shear stresses.

• Introduction of saltation sediment at the upwind edge of the working section is important to simulate the effect of particle bombardment on the test surface.

Modern field wind tunnels have concentrated on achieving aerodynamic requirements in order to produce both realistic wind flow and sediment transport characteristics (Greeley and Iverson, 1985). As a result, they commonly exceed 10 m in length and have a 1 m² cross sectional area (height being greater than width), a size ideal for large, homogenous sites such as cultivated paddocks. But in the pursuit of meeting aerodynamic criteria, the practicality of these wind tunnels is often compromised. Maurer et al., (2006), who emphasised the need to meet aerodynamic criteria of the three functional design requirements outlined above, also documented the considerable logistical difficulties of moving a large truck/trailer-based wind tunnel through the landscape and then locating suitable sites capable of housing the equipment—sites which not only need to be free of vegetation to minimise aerodynamic noise, but also flat to reduce structural stress on the tunnel and avoid leakage of air. Such field logistics are common to large field wind tunnel studies: the impact of the logistics depends on the 'footprint' size of the tunnel.

Historically, field tunnels have predominantly been used in agricultural settings where the constraints on replicating natural wind flow are concentrated on the physical design of the tunnel. In natural settings such as rangelands, landscape elements increase the difficulty of replicating natural wind flow. The size of the tunnel limits where it can be positioned, with most portable field wind tunnels smoothing out the variability created by intricate spatial variations in soil surfaces (see Chapter 5).
Smoothing such surface features is undesirable, as each surface feature has its own erodibility.

Table 4.1 Historical perspective of a number of wind tunnels used to monitor sediment movement and soil erodibility.

<table>
<thead>
<tr>
<th>Source</th>
<th>Project Aim</th>
<th>Physical Parameters of the Wind Tunnel</th>
<th>Outcomes and Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zingg (1951)</td>
<td>To develop and describe a portable wind tunnel</td>
<td>A portable 3 foot square wind tunnel with a total length of 30 feet. A heavy-duty 3 foot ventilating fan with adjustable vane inlet control diffused through screens and a honeycomb straightening device.</td>
<td>Establish design criteria for portable wind tunnels. Defined 7 factors of good design: 1) steady flow air stream; 2) generation of variable wind speeds; 3) durability; 4) safety; 5) large enough to allow representative sampling over field surface; 6) portable; and 7) easy to assemble and dismantle between sites.</td>
</tr>
<tr>
<td>Chepil (1953)</td>
<td>To measure the relative erodibility of soil</td>
<td>Exposed a tray of soil (5 feet long 8 inches wide) in a laboratory wind tunnel.</td>
<td>Identified that variations in soil texture caused variation in soil erodibility. Defined the wind tunnel erodibility index (l), which is under standard wind tunnel conditions and is expressed in tones/acre.</td>
</tr>
<tr>
<td>Chepil (1959)</td>
<td>To evaluate different types of wind erodibility</td>
<td>Laboratory wind tunnel (as per Chepil 1953)</td>
<td>Believed that tunnels could only express the quantity of soil removed NOT the effect of abrading soil particles that bounce along the soil surface.</td>
</tr>
<tr>
<td>Gillette (1978)</td>
<td>To determine wind erosion threshold velocities.</td>
<td>Open-bottomed portable wind tunnel: 150 mm square, by 2.4 m length. Tunnel has 5:1 contraction section with honeycomb flow straightener and a conical diffuser.</td>
<td>Determined that the size distribution of the surface material is important in determining the threshold velocities. Increase n particle mass lead to decrease in erodibility. Described turbulent boundary layers for all walls and the floor. Identified increased centre velocities with increased frictional slowing of air near the boundaries.</td>
</tr>
<tr>
<td>Raupach and Leys (1990)</td>
<td>To define the aerodynamic criteria of portable wind tunnels and to compare two alternative designs</td>
<td>Portable field wind tunnel. Flow conditioning length of 4 m followed by a working section 7.2 m, 1.2 m wide and 0.9 m high. Turning vanes to generate artificial gustiness. Flow velocity adjusted by changing the engine speeds.</td>
<td>Defined characteristics required by tunnels: 1) Reproduce the mean wind profile in the natural atmosphere 2) Correctly scale surface shear stress with wind speed 3) Provide a realistic vertical turbulence intensity and scale 4) Provide uniform flow to avoid local scouring 5) Preserve gusts 6) Allow the introduction of saltating grains</td>
</tr>
<tr>
<td>Shao and Raupach (1992)</td>
<td>To quantify the overshoot of saltation in portable wind tunnels.</td>
<td>Portable wind tunnel with a working section of 17 m long. 1.15 wide and 0.9 m high.</td>
<td>Considerable distance is required for the process of saltation to reach equilibrium. Before equilibrium was reached, the initial high wind speeds induced rapid saltation i.e. overshoot. Short wind tunnels (&lt;15 m) will overestimate sediment flux.</td>
</tr>
<tr>
<td>Pietersma, Stetler &amp;</td>
<td>To develop a portable wind</td>
<td>Portable wind tunnel, 13 m long, 1 m wide and 1.2</td>
<td>Generated a 1 m high boundary layer by conditioning the flow and using a non-</td>
</tr>
</tbody>
</table>
Despite the apparent clash of objectives—big enough to replicate air flow yet small enough to test discrete surface features—it is the larger field wind tunnels which are commonly used to determine the erosion rates of different crust surfaces. Generally though, the research questions are aimed at the landscape scale of erosion. For example, Nickling and Gillies (1989) used a large tunnel to investigate the erodibility of different physical crusts across a large playa (claypan). Their results identified the average sediment flux from a crusted surface, as the spatial heterogeneity of the crust forms found on the playa could not be measured individually with a large tunnel.

Another approach to answer landscape scale questions is to use laboratory wind tunnels in which uniform test beds of the desired soil surface can be inserted into the tunnel floor (McKenna Neuman et al., 1996; McKenna Neuman and Maxwell, 1999; Rice & McEwan, 2001).

A small wind tunnel constructed by Gillette (1978) offered the most innovative and powerful tool for studying soil surfaces in situ at a smaller scale. The tunnel was unique in having a comparably small cross section of only 150 mm x 150 mm and a length of just 3 m. Acknowledging the potential of this smaller-sized tunnel, Belnap and Gillette (1997, 1998) used it a decade after its construction to characterise the threshold friction velocities on a range of biological crusted surfaces. Belnap and Gillette did not measure emission rates, possibly because of a perceived failure of the smaller tunnel to meet the aerodynamic requirements so eagerly sought in the designs of larger tunnels.

The ambit of this study called for methods that could determine the erosion rates of different source areas that included both physical and biological crusts. It was decided that a small wind tunnel, similar to that designed by Gillette, could be designed to meet the field parameters. As a result, the micro wind tunnel (MWT) was specifically designed to sample small plot sizes and fit around vegetation commonly associated with biological crusts. The size of the tunnel also meant the crust surface did not have

<table>
<thead>
<tr>
<th>Source</th>
<th>Project Aim</th>
<th>Physical Parameters of the Wind Tunnel</th>
<th>Outcomes and Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saxton (1996)</td>
<td>tunnel that closely represents the actual erosion processes in an open field</td>
<td>m high. 33 kW engine turning a 1.2 m industrial fan, aerodynamically designed</td>
<td>uniform shear grid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Turbulence profiles were maintained beyond a downstream distance of three times the tunnel height</td>
<td>Lateral uniformity of wind speed achieved</td>
</tr>
</tbody>
</table>
to be damaged for successful operation. Dune surfaces could also be assessed with the MWT due to its portability.

4.3 Design questions

The benefits of a small tunnel include:

- the ability to test different source areas with high spatial variation
- the ability to be operated by one person; and
- high portability.

The cost of these benefits, however, is that airflow and sediment entrainment within the tunnel may not conform to reality. To determine the physicality of the MWT, a series of research questions was posed to describe the airflow, saltation layer, and sediment flux in the MWT:

- Does the MWT produce repeatable wind speeds and uniform flow in the Y plane?
- What is the shape of the wind speed profiles, do they respond to roughness, and are they logarithmic?
- What is the performance of the saltation injection system?
- Is the sediment trap efficient and isokinetic?

Following a description of the design and components of the tunnel, the answers to these questions form the basis of the second part of this chapter.

4.4 MWT design

The MWT is a suction-type tunnel constructed from a single 3,055 mm length of aluminium box tube 100 mm wide and 50 mm high. The overall design of the tunnel is shown in Figure 4.1 and a photo of the completed tunnel in the field is shown in Figure 4.2.

The tunnel has seven key components, listed below and shown in Figure 4.1:

- motor and speed regulation
- transition section
- working section
- exhaust section
- sediment trap
- saltation injection tube
- wind-speed sensors

Figure 4.1 Schematic of the various components of the Micro wind tunnel (MWT)
4.4.1 Motor and speed regulation
The primary tunnel motor is a 0.55kW electric 240-volt induction motor which turns an EAR 280 mm axial blower. The motor is attached in such a way as to create suction through the tunnel, generating a velocity range of 6–18 m/s. The velocity of the MWT is controlled via a calibrated baffle plate on the blower exhaust. Near-complete blockage of the exhaust retards the tunnel velocity while no blockage allows maximum tunnel velocity.

4.4.2 Transition section
The transition section functions to organise and enhance the airflow. At the entrance, air is drawn in through a opening wider than the tunnel (220 x 50 mm), forcing the air to contract and stabilise. This is followed by an 1,100 mm transition section which organises the flow and introduces saltation material into the air stream. The transition section is made from unmodified aluminium box tube.

4.4.3 Working section
Downwind of the transition section is the 1,000 mm-long working section. In this section, the aluminium floor has been removed allowing sampling of the test surface and the roof consists of a Perspex viewing window. Keyholes have been drilled in the roof at distances of 100, 450 and 900 mm from the start of the working section to
allow insertion of the velocity-measurement devices. When not in use, the keyholes are plugged with an internally flush silicone plug.

4.4.4 Exhaust section

Downwind of the working section is the 705 mm-long exhaust section. Within this section tunnel velocity is measured, sediment is sub sampled for measurement, tunnel flow control occurs, and the cross-section changes from rectangular to circular to facilitate connection to the induction motor.

Tunnel flow is controlled via a bypass valve that redirects the flow from the roof of the sediment-sampling section to the inlet at the front of the tunnel. This is used to start and stop the flow through the working section while keeping the blower running. The tunnel is connected to the induction motor via a 76 mm-diameter hose.

4.4.5 Sediment trap

A vertical slot sampler located on the centre line of the tunnel is used to sub sample the tunnel airflow and collect sediment. The vertical slot is 10 mm wide and 50 mm high, representing 10 percent of the tunnel’s cross-sectional area. The air from the sediment sampler is drawn vertically through a 38 mm hose to the sediment filter box, which houses 125 mm-diameter glass-fibre filter papers with 0.1 µm pores.

The airflow through the sediment sampler, hose and filter paper occurs via a second variable-speed motor. This motor is quasi-isokinetic, with tunnel speed manually calibrated by bleeding air in the exhaust line of the second motor.

4.4.6 Saltation injection system

Saltation is injected into the tunnel on demand via the saltation silo. This silo is a 40 mm-diameter acrylic tube with a tapered end to allow positioning at the entrance to the tunnel. The silo has a 2 mm-diameter hole in the base and a 3 mm-diameter tapered stainless-steel rod with which to block the hole. The stainless-steel rod is attached to a solenoid that lifts the rod 10 mm vertically. This solenoid is electrically connected to the bypass valve so that it may be activated with the bypass valve. In this way, saltation injection is synchronised with the start of tunnel flows.
4.4.7 Wind speed sensors

Two types of wind speed sensors were used: traditional pitot tubes and pressure ports. Velocity was measured by 1 mm dynamic port Dwyer pitot tubes connected to pressure transducers. The pitot tubes could be positioned in a number of arrangements throughout the tunnel. The position of each tube was noted as an x, y and z position to denote (in order) longitudinal, lateral and vertical position coordinates, with the following origins: x = 0 at the leading edge of the working section; y = 0 at the left hand side of the tunnel as looking in the direction of wind flow; and z = 0 at the test bed/ground surface (Figure 4.3).

![Figure 4.3 Positioning of pitot tubes for velocity determination experimentation](image)

Velocity measured using pressure ports allowed an alternative method of measuring friction velocity to be tested. Brass tubes with an internal diameter (ID) of 3.3 mm were fixed flush to the inside surface of the roofline, 200 mm apart in the working section and 300 mm apart in the lengthened transition section. These ports were connected directly to a pressure transducer with the positive side of the transducer attached to the port downwind of the sediment sampler slot and the negative side of the transducer at any one of the other nine ports.

Temperature of the tunnel airflow and barometric air pressure were measured every second and averaged over 2 minutes for the calculation of air density.
4.5 Experimental development of the wind tunnel functionality

4.5.1 Does the MWT produce repeatable wind speeds and Y-plane uniform flow?

Wind speeds

Knowledge of the wind tunnel’s operating velocity is needed to determine the susceptibility of a soil surface to wind erosion. In addition, any simulation of wind must represent a range of wind speeds to show the variable soil-surface responses. The wind speeds achieved by a wind tunnel must be not only measurable, but repeatable.

To determine the velocity range of the MWT, flow passing over a control surface (a sheet of 4 mm ABS plastic, ‘glassy’ side up) was measured. In the first instance, measurement was made via a standard technique that uses pressure transducers in conjunction with pitot tubes (as described above). During all testing, the tunnel was operated as it would be in the field during sampling. As such, both the tunnel and trap motors were run concurrently and the filter paper was replaced with each run. The proportion of the exhaust baffle plate that was covered was incrementally changed seven times. Each baffle position was replicated nineteen times and the wind tunnel was run for one minute per replicate. Each baffle position created a different wind speed ranging from 5–18 m/s routinely with excellent reproducibility (Figure 4.4).
Figure 4.4. Range of wind speeds \((x = 900, y = 50, z = [15, 25, 35])\) produced on the smooth test surface (mean ± S.E; \(n = 19\)).

Y-plane uniformity

The uniformity of flow across the tunnel (cross–sectional, or Y plane) was also tested with pitot tubes. Ideally, a tunnel should produce uniform flow across the Y plane without any jet streams or bias. In order to determine whether this criteria was met by the MWT, three degrees of surface roughness were tested:

- a smooth surface (as above)
- a medium surface created by gluing a 110 mm-wide piece of 40 grit sandpaper to a board; and
- a coarse surface created by recessing 539 glass marbles (each 12 mm diameter) into the 11mm-deep groove of a test board, allowing a 1 mm protrusion.

Three pitot tubes were used in a rake formation and clamped 5 mm apart. Three y positions were used (25, 50 and 75 mm). Z was measured at nine heights (5, 10, 15, 20, 25, 30, 35, 40 and 45 mm). Sampling occurred at \(x = 100, x = 450\) and \(x = 900\) mm. Contour plots with 0.2 m/s resolution were plotted using R analysis and graphic software (Ihaka and Gentlemann, 1996).
The Y-plane contour plots for the three test surfaces indicate that the floor and roof are both sources of drag. As indicated by the velocity profile development figures, floor-surface roughness increases the drag, decreasing the near-ground velocities and resulting in an increase in the roofline velocities. The implications of this effect are discussed below. Slight preferential flow lines do exist down the right hand side of the tunnel but have minimal impact on the soil surface (Figure 4.5).

![Contour plots for smooth, medium and rough test surfaces showing cross-sectional profile of the tunnel.](image)

**Figure 4.5** Contour plots for smooth, medium and rough test surfaces showing cross-sectional profile of the tunnel. Wind direction is away from reader. (x = [100, 450, 900], y = [25, 50, 75] z = [5, 10, 15, 20, 25, 30, 35, 40, 45])

### 4.5.2 What is the shape of the wind speed profiles, do they respond to roughness, and are they logarithmic?

Frictional forces close to the Earth’s surface affect natural wind flow. As a result, wind speeds are slower close to the soil surface and get faster with height. When these wind speeds are measured at various heights, a log normal wind profile is generated (Greeley and Iversen, 1985). Ideally, if a wind tunnel is to represent natural wind flows it should likewise produce a log normal wind profile which responds to changes in surface roughness. This is in addition to a consistent cross sectional flow with no obvious jet streams, as discussed above. To characterize the wind speed profiles
across different surface roughness elements, a mid-range wind speed, created by using baffle position 5, was tested on the three surface roughness test surfaces described above. Wind speed profiles were calculated by measuring seven heights within the tunnel. As the pitot rake only had three pitot tubes, this twice required raising the entire rake by 5 mm.

**Wind speed profiles**

Wind speed profiles were characterized by positioning three pitot tubes spaced 10 mm apart at $x = 900$ mm, $y = 50$ mm and $z =$ seven heights (10, 15, 20, 25, 30, 35 and 40 mm). Development of the velocity profile along the length of the working section was characterized by sampling at $x = 100$ (upwind) and 900 mm (downwind), $y = 50$ mm and $z =$ seven heights (10–40 mm). Again, baffle position 5 was used for all three test beds and the experiments were replicated five times.

**Shape of the wind speed profiles**

All profiles lacked the desirable log normal wind profile. Instead, a profile was produced that appears to reflect friction, not only on the floor surface, but also on the tunnel roof (Figure 4.6):

- The smooth test surface produced a profile that reached maximum velocity at the centre point (i.e. 25 mm high) with greater resistance at the roof than the smooth surface of the ABS sheet.
- The medium-roughness test surface (sandpaper) created a profile that reflected a floor surface rougher than the roof (i.e. slower velocities at the floor), however maximum velocity was still maintained at the centre point.
- The roughest test surface resulted in considerably slower wind speeds at the ground than the roof. The maximum velocity was slightly higher than the tunnel midpoint, peaking at 30 mm. Interestingly, the roofline yielded significantly faster speeds than when tested with the smooth (control) surface. This shifting of the profile shape reflects the compensation in one part of the tunnel for increasing surface drag (and therefore slowing air velocity near that surface as a result) in another when there is a standard volume of air being sucked through the tunnel per minute.
Despite the lack of a log normal profile, the wind speed profiles develop strongly as the wind moves downwind 800 mm between the two measurement points in the working section. This demonstrates that wind speed profiles are sensitive to changes in the surface roughness. At position \( z = 5 \) mm, the velocities across each test surface increased from the upwind position \( x = 100 \) mm to the downwind position \( x = 900 \) mm (Table 4.2). Velocities measured near the floor surface decreased as the surface roughness increased. The range of velocities measured near the roofline also changed with the test surface roughness. Initially, the smooth roofline and ground velocities are equal, but as the roughness increases, the roofline velocities also increase (Table 4.2).

<table>
<thead>
<tr>
<th>Test Surface</th>
<th>Roughness</th>
<th>( Z = 5 ) (mm)</th>
<th>( Z = 25 ) (mm)</th>
<th>( Z = 45 ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS plastic</td>
<td>Smooth</td>
<td>6.9 – 7.0</td>
<td>8.2 – 8.3</td>
<td>6.9 – 7.0</td>
</tr>
<tr>
<td>Sandpaper</td>
<td>Medium</td>
<td>6.7 – 6.9</td>
<td>8.1 – 8.5</td>
<td>6.8 – 7.2</td>
</tr>
<tr>
<td>Marbles</td>
<td>Rough</td>
<td>6.0 – 6.8</td>
<td>8.3 – 8.6</td>
<td>6.9 – 7.5</td>
</tr>
</tbody>
</table>

As described above, the MWT provides a repeatable range of wind speeds (more accurately termed velocity, \( U \)) but does not produce a log normal wind speed profile. The tunnel geometry, in particular its height, does not allow profile development.
Traditionally, the log profile is used to calculate soil surface descriptions such as drag and friction velocity (u*). Three underlying features need to occur for the development of log profiles:
1. The boundary layer must be fully developed
2. The air parcels need to be in constant stress; and
3. The profile needs to be above the roughness element.

The boundary layer can never fully develop in the MWT as it does in open-air scenarios due to the restricted length of the MWT. In fact, the MWT displays behaviour akin to a duct and we can better understand the behaviour of the wind speed profiles of the tunnel if we consider the theoretical movement of air flow in a duct.

The internal flow of a duct is constrained by the bounding walls, and the viscous effect extends through, meets and permeates the entire flow. There is an entrance region where a nearly inviscid upstream flow converges and enters the duct. Viscous boundary layers grow downstream, retarding the axial flow $u(r,x)$ at the wall, thereby accelerating the centre-core flow to maintain the incompressible continuity requirement (White, 1994).

$$Q = \int u \, dA = \text{constant.}$$  \hspace{1cm} (4.1)

At a finite distance from the entrance, the boundary layers merge and the inviscid core disappears. The tube flow is then entirely viscous, and the axial velocity adjusts slightly further until at $x = L_e$ it no longer changes with x and is said to be fully developed, or $u \sim u(r)$. Downstream of $x = L_e$ the velocity profile is constant, the wall shear is constant, and the pressure drops linearly with x, for either laminar or turbulent flow.

Dimensional analysis shows that the Reynolds number is the only parameter affecting entrance length:

$$R_e = wD_H$$  \hspace{1cm} (4.2)

When $D_H$ is calculated by $(4 \times \text{Area})/((2 \times \text{width}) + (2 \times \text{height}))$, the MWT has Reynolds numbers ranging from $26,500 < R_{e[MWT]} < 80,000$. By utilising the Reynolds numbers and the relative roughness ratios ($26,500 < R_{e[MWT]} < 80,000; 0.03$), the flow in the MWT can be categorised by the Moody Chart (Schetz and Fur, 1999) as being
In ducts with turbulent flows, the boundary layers grow faster, and the \( L_e \) is relatively short according to the approximation:

\[
L_e/d \sim 4.4 \, \text{Re}_d^{1/6}
\]  

Therefore, the MWT does not support a log profile because the boundary layer cannot be fully developed. The roofline is too low creating conflicting drags from all four surfaces, and the cross-sectional area results in turbulent flow of low Reynolds numbers.

However, to make results comparable with other wind tunnel work, a meaningful descriptor of wind flow is required. Friction velocity \((u_*)\) is a frequently-used measure describing the wind speed required to initiate sediment movement. The next section will investigate an alternative method of measuring \( u_* \): the integral momentum method.

**An alternative method for measuring velocity**

Having identified that air flow in the MWT behaves more like air flow in a duct than a larger tunnel, an alternative measurement of velocity needed to be found before friction velocity could be calculated. Due to the encroachment of the inviscid core into the working section, the tunnel transition section was lengthened by 1,000 mm. Pressure ports were placed along the centreline of the roof, 200 mm apart in the working section and 300 mm apart in the transition section. Five ports were placed in the working section and seven in the transition section. Each port consisted of a 3.3 mm ID brass tube fixed flush to the inside surface of the roofline. A pressure transducer was connected directly to pressure ports in the roof of the tunnel. The negative side of the pressure transducer was attached to port \( x = 50 \) mm, and the positive side of the pressure transducer was attached to port \( x = 900 \) mm.

Simulations consisted of one-minute run times replicated three times for five wind speeds (baffle 2.5, 3.5, 4, 5 and 6) over the smooth ABS plastic surface. Results showed velocity measurements with the pressure ports routinely ranging from 8–17 m/s with excellent reproducibility (Figure 4.7).
Figure 4.7. Range of velocities measured with the pressure port method produced on the smooth test surface (see bars shown. n = 3).

**Integral momentum—an alternative way to measure friction velocity**

Once the entrance length, and therefore the distance at which flow in the duct becomes fully developed, were identified, Hughes et al., (in press) suggested that friction velocity could be determined by calculating the coefficient of drag. The coefficient of drag can be calculated by measuring pressure gradients and using an integral momentum balance. Theoretically, in a fully developed duct flow, the integral momentum balance is:

\[
\int_{\text{circumference}} \rho u_*^2 \, dr = -A \frac{dp}{dx} \tag{4.4}
\]

where \(u_*\) is the friction velocity, \(\rho\) is air density, \(\rho u_*^2\) is the drag on the surface, \(dr\) is a length increment running around the tunnel circumference in a plane normal to the flow, \(A\) is the area of the tunnel cross-section, and \(dp/dx\) is the stream-wise pressure gradient.

Therefore, in a rectangular duct of height \(Z\) and breadth \(Y\):

\[
(2Z + 2Y) u_{(Allf)}^2 = -\frac{YZ}{\rho} \frac{dp}{dx} \tag{4.5}
\]
where $u_{*\langle All\rangle}$ is an area-weighted average friction velocity for all surfaces around the tunnel circumference. The floor contributes a length $Y$ to this average, and the sides and roof together contribute a length $(2Z + Y)$. Hence:

$$\left(2Z + 2Y\right)u_{*\langle All\rangle}^2 = Yu_{*\langle r\rangle}^2 + \left(2Z + Y\right)u_{*\langle s\rangle}^2$$

(4.6)

where $u_{*\langle r\rangle}$ is the friction velocity for the rough floor, and $u_{*\langle s\rangle}$ is the friction velocity for the smooth sides and roof. The task is to infer $u_{*\langle r\rangle}$ from measurements of $dp/dx$. This requires rearranging the last equation as:

$$u_{*\langle r\rangle}^2 = \left(\frac{2Z + 2Y}{Y}\right)u_{*\langle All\rangle}^2 - \left(\frac{2Z + Y}{Y}\right)u_{*\langle s\rangle}^2$$

(4.7)

Once the drag coefficient is known, the $z_o$ can be calculated:

$$Zo = \left(\frac{U*}{U_z}\right)^2$$

(4.8)

Substitute $U = \frac{U*}{k \log}$

Once reworked becomes:

$$k = 0.4, \ z = 25 \ mm$$

Pressure gradients were used to test these theoretical workings.

**Estimating friction velocity and roughness length using pressure gradients**

To test the integral momentum method, the pressure gradient was calculated for the transition and working sections of the tunnel. Testing was performed on three test surfaces by placing full-length test beds throughout the entire tunnel length. Unlike previous testing where just the working section surface was changed, it was important to keep the same roughness element in both the transition and working sections. Therefore, full-tunnel-length pieces of 2 mm-thick PVC sheet (100 mm W, 2,200 mm L) were used as the base for different roughness treatments.

Three surfaces were tested as described below:

1. **Smooth**: PVC (2 mm thick, 100 mm W, 2200 mm L) unaltered
2. **Sand**: Sand was glued to the PVC surface with spray adhesive. The sand had a unimodal particle-size distribution moding at 213 µm.

3. **Bubble wrap**: Small-sized bubble-wrap film glued to the PVC surface. Individual bubbles had a diameter of 10 mm and a height of 5 mm.

The all-surface $u^{(\text{AllSf})}$ (surface drag on all four sides of the tunnel) was calculated from the pressure gradient, and then the floor friction velocity $u^{(f)}$, determined using the average of $u^{(\text{AllSf})}$ and $u^{(s)}$ across both the transition and working sections, and equation 4.7.

As the test surface roughness increased, so too did the rough-surface $u^{(f)}$ (Table 4.3), indicating that the integral momentum method was successful in partitioning the drag coefficient for the tunnel floor.

**Table 4.3 Coefficient of drag parameters of the MWT floor as calculated using the integral momentum technique. The derived values for $u^*$ and Zo are shown.**

<table>
<thead>
<tr>
<th>Tunnel Speed</th>
<th>Test surface</th>
<th>Floor Coefficient Drag (unitless)</th>
<th>Floor $u^*$ (m/s)</th>
<th>Floor Zo (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.8 m/s</td>
<td>Smooth</td>
<td>0.0023</td>
<td>0.32</td>
<td>0.006</td>
</tr>
<tr>
<td></td>
<td>Sand bed</td>
<td>0.0034</td>
<td>0.40</td>
<td>0.026</td>
</tr>
<tr>
<td></td>
<td>Bubble wrap</td>
<td>0.0059</td>
<td>0.52</td>
<td>0.139</td>
</tr>
<tr>
<td>11.6 m/s</td>
<td>Smooth</td>
<td>0.0021</td>
<td>0.54</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>Sand bed</td>
<td>0.0034</td>
<td>0.68</td>
<td>0.027</td>
</tr>
<tr>
<td></td>
<td>Bubble wrap</td>
<td>0.0056</td>
<td>0.86</td>
<td>0.117</td>
</tr>
</tbody>
</table>

The values for $u^*$ are comparable to those calculated by Shao and Raupach (1992) for a large wind tunnel (Table 4.4). These results suggest that the MWT produces appropriate drag levels for the wind speeds produced in the tunnel. In the former study, a natural logarithmic wind profile was produced, ensuring realistic aerodynamic forces on saltating grains over a sand bed similar in size to the MWT. Velocity was measured at 0.28 m in their study with the values for $u^*$ listed in Table 4.4. For comparison, the velocity at the same measurement height as used in the MWT is also given (Table 4.4).
Table 4.4 Comparison of $u^*$ between the MWT and a large log normally distributed tunnel used by Shao and Raupach (1992).

<table>
<thead>
<tr>
<th>U (m/s)</th>
<th>$u_*$ (m/s)</th>
<th>$u_*$ (m/s)</th>
<th>$u_*$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.8</td>
<td>0.40</td>
<td></td>
<td>0.35</td>
</tr>
<tr>
<td>8.5</td>
<td></td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td>11.5</td>
<td></td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>11.6</td>
<td>0.68</td>
<td></td>
<td>0.72</td>
</tr>
<tr>
<td>12.5</td>
<td></td>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>

Extension of integral momentum

As mentioned previously, wind tunnel flow conditions are traditionally compared by using friction velocity ($u_*$) as calculated with log normal profiles. Friction velocity can then be related to air velocity at 10 m. The theoretical workings of calculating friction velocity using pressure gradients indicates that the results of the MWT could be extrapolated to the results of larger tunnels, and hence 10 m as commonly reported in the literature.

However, before this could occur, further experimentation was required to ensure the modifications made to the tunnel for the theoretical testing were usable in the smaller field-tunnel configuration. The previous $dP/dx$ testing was conducted on a lengthened tunnel to reduce the impact of the inviscid core on readings and allow the placement of roughness elements along the entire length of the tunnel. For field operations, the tunnel was 1 m shorter and the floor in the transition section was smooth aluminium.

Three hierarchical questions existed, viewed as a dichotomous key with statistical significance at each step determining the pathway of further experimentation. Figure 4.8 indicates the line of enquiry, with the desirable outcome of a workable application for calculating $u_*$ and $z_o$ in field-collected samples.
There was no significant difference in pressure readings by restricting the roughness element to the working section only (ANOVA: $F_{1,29} = 0.46$, $P = 4.35$). Reducing the tunnel length by one metre to the length used in the field was also not significant (ANOVA: $F_{1,29} = 0.91$, $P = 4.35$). However, different roughness elements (the different test surfaces) produced differing drag pressure within the tunnel (ANOVA: $F_{2,44} =139$, $P = 6.6 \times 10^{-16}$) resulting in the need to produce a $u^*$ relationship for each of the roughness surfaces (Figure 4.9).
4.5.3 What is the performance of the saltation injection system?

A fundamental component of wind erosion is the bombardment of the soil surface by saltating soil particles. These particles abrade the soil surface, frequently fracturing it and releasing more soil particles into the air stream. While wind speeds above threshold velocity will initiate movement of naturally loose sediments, it is advantageous to control the addition of saltation sediment to simulate the effect of saltation coming from an upwind source area. Wind tunnel saltation injection systems need to deliver a certain quantity of sediment over a known time. The rate at which this material is added both under static wind conditions and through a range of wind speeds differs, and is described here.

A commercially-available sand blasting sediment, 50N (Commercial Minerals), was used in the saltation injection system. This sand has a unimodal particle-size distribution moding at 213 µm (as determined with Multisizer 3 analysis). To calculate the static flow rate, the time a known weight of sand took to discharge from the saltation silo was recorded. Determination of saltation feed rate associated with change in velocity (dynamic saltation feed rate) was made by timing complete discharge of pre-weighed samples at different tunnel velocities (6–18 m/s). Each
velocity was replicated five times. Both tunnel motors were operating, a clean filter paper was in place, and tests were performed over the smooth test surface.

A static saltation feed rate of 6.1 g/m/s (se of 0.1 g/m/s) remained constant across a range of sediment weights. This rate is comparable to Pietersma et al., (1996) with an adjustable saltation feed rate of 0.25–6.6 g/m/s. The dynamic saltation feed rate increased with increasing tunnel velocity, ranging from 7.5–10.8 g/m/s. A strong positive non-linear relationship \( y = 6.1e^{0.0357x} \) \((r^2 = 0.99, p = 0.04)\) was found for wind speeds between 0–16 m/s (Figure 4.10).

![Figure 4.10 Dynamic saltation feed rates resulting from increase in tunnel velocity.](image)

Treatments used in the field and laboratory incorporated changes in tunnel velocity. As indicated, this would result in the saltation feed rates varying according to tunnel velocity, which would be unacceptable from an experimental perspective as the number of ‘artificial’ saltation impacts needed to be kept constant. To this effect, a constant mass of sediment was used instead of trying to keep the feed rate constant. This was a simple, practical solution which had the effect of delivering the same number of impacts to the surface. The momentum delivered to the surface is, however, greater at higher wind speeds, as would be the case in the field. Therefore,
only the wind speed and not the number of particles used to abrade the surface were changed.

Is the sediment trap efficient and isokinetic?

The MWT uses two motors: one to create the main tunnel flow (i.e. the wind speed) over the soil surface, and the second to sub sample the tunnel flow for sediment collection. The wind velocity at the sub-sampling inlet should ideally be the same as the main tunnel velocity (i.e. isokinetic). If the sub-sampling inlet has greater velocity than the tunnel, over-sampling could occur due to greater air intake by the sub sampler. By the same token, a lower velocity in the sub-sampling inlet would result in under-sampling.

The sub-sampling inlet has a cross section of 10 x 50 mm, representing 10 percent of the cross-sectional area of the tunnel. Given that wind flow in the Y plane (Figure 4.5) does not show any major bias, and that we assume the air flows created by the two motors are isokinetic, sediment collected on the filter paper should represent 10 percent of the total amount of sediment carried in the air stream. In order to test this assumption, the isokinetic flow needed to be calculated to ensure that inconsistent results in air flows were not modifying the collection efficiencies.

Isokinetic flow

Isokinetic flow between the trap motor and the tunnel flow is achieved manually by bleeding air from the trap motor line. Pitot tubes monitor pressure differentials simultaneously in the tunnel and the trap line. In the trap line, the pitot tube is placed 200 mm downwind of the entrance. In the tunnel, the pitot tube is positioned mid-point on the centreline, 900 mm from the start of the working section (x = 900, y = 50, z = 25).

Pressures from the pitot tubes are converted to velocities in conjunction with measured tunnel temperature and barometric pressure. The trap line has a different geometry (38 mm ID) to the trap entrance (10 x 50 mm), therefore sediment trap velocity is converted to the trap inlet velocity. Multiple calibration runs in the laboratory using the three test surfaces—smooth (ABS), medium (sandpaper) and rough (marbles)—identified the number of bleed valves required to be opened in the
trap line to balance the flows. A near 1:1 relationship was achieved between the two motors in terms of velocity.

**Collection efficiency**

Calibration runs were conducted in the laboratory to determine the collection efficiency of the MWT. Four wind speeds were tested over the smooth (ABS) test surface, and each test was repeated five times. Thirty grams of abrader sand were added to the saltation injection system and released at the start of the one-minute run. Both motors were run, preset to the isokinetic settings, with pre-weighed GF/A filter papers of 1.6 micron pore diameter (Millipore GF/A) in place. Pitot tubes measured pressure both in the trap line (200 mm downwind of the entrance) and in the tunnel (x = 900, y = 50, z = 25). Collected sediment was weighed and expressed as a percentage of the theoretical weight: 3 grams.

On smooth test surfaces, wind speeds greater than 10 m/s had collection efficiencies of more than 90 percent (i.e. more than 9 g of the expected 10 g were collected on the filter paper), however wind speeds less than 10 m/s reduced efficiency to 85 percent (Figure 4.11).

![Graph](image)

**Figure 4.11.** Collection efficiency and velocity ratio of 4 wind speeds over the smooth test surface (n = 5).
The addition of a saltation cloud broke down the isokinetic flow, with wind speeds less than 10 m/s under-sampling and wind speeds greater than 10 m/s over-sampling (Figure 4.11). Collection efficiencies were corrected by multiplying the sediment mass by the velocity ratio (the ratio of the tunnel velocity to the inlet velocity). A ratio of 1 represents isokinetic flow, less than 1 indicates over-sampling by the sediment trap, and greater than 1 indicates under-sampling of the sediment trap.

4.6 Summary

By developing the MWT, small patches of variable soil surfaces were able to be measured. The MWT is small, portable and operable by one person. These attributes ensured that discrete surface features could be measured, unlike larger tunnels where differences between discrete surface features are homogenised due to the larger surface area.

In brief, the MWT produced velocities ranging from 6 to 18 m/s with high reproducibility. The velocity profiles showed an orderly progression downwind, and the contour plots showed a good distribution in the yz plane. Flow in the MWT was inhibited by the lack of (or very small) boundary layer and the frictional influence of the sides and roof. These factors resulted in the MWT not being able to develop a log normal profile. This represented a deviation from standard, larger tunnels which use a log normal profile to calculate friction velocities, the link to real wind processes.

Theoretical calculations and follow-up experimentation demonstrated that by using the integral method (Hughes et al., in press) to measure drag coefficients, \( u^* \) could be measured for a given core velocity in the MVT. The measurement of drag coefficient, therefore, provided a robust property of the flow, allowing the calculation of both sensible \( u^* \) and surface-roughness measures in the MWT. Extrapolation of the technique to the field MWT was shown to be possible, and the results were comparable to published accounts of another wind tunnel.

Saltation feed rate was at the optimal rate of 6.1 g/m/s, however this was influenced by velocity changes in the tunnel. To overcome this in the field, known amounts of sediment were added. Collection efficiency (i.e. collection on the filter papers of 10 percent of any saltation material added) was high (in the mid-90 percent range).
The MWT will be used as one of the erodibility measurements made throughout the next chapter.
Chapter 5. Spatial Patterns of Soil Surfaces

5.1 Introduction

Worldwide, soil surfaces across arid lands have variable susceptibilities to wind erosion (Gillette et al., 1982). The diversity of soils and surface conditions are the key to this variability. For example, dunes and claypans (McTainsh et al., 1999; Hupy, 2004; Reheis, 2006) are two arid landforms that contribute significantly to atmospheric dust levels (McTainsh et al., 1999). While dunes are highly erodible, claypans are extremely variable. Variation is often recorded through sediment flux data either collected with sediment traps (McTainsh et al., 1999; Hupy, 2004), simulated with wind tunnels (Nickling and Gillies, 1983), or modelled (Butler et al., 1996). This variation in flux data, although commonly attributed to changes in the erodibility of the soil surface, is often collected at a scale that precludes partitioning of different surface features to understand their contribution to erodibility (Fryrear, 1990). The contribution of surface features to erodibility is not well understood; improving our understanding of erodibility controls is a key aim of this thesis. The spatial patterning of a soil surface is considered to be a key to understanding erodibility in arid landscapes.

Crusts are known to play an important role in controlling erodibility. The type and distribution of soil crusts are instrumental in protecting the soil surface (Leys, 1990; Houser and Nickling, 2001; Gillette et al., 1982). On claypans, both physical and cyanobacteria crusts frequently exist at the same locality, although the distinction between the two is often overlooked. This is unfortunate, as each crust type has both morphological differences as well as different erodibilities. This is due, in part, to each crust type having a different formation processes, akin to inherited traits.

Despite the role of crusts in controlling erodibility, this factor is often overlooked or over-simplified in wind erosion studies. Broad scale wind erosion studies consider both atmospheric and land-based parameters. Parameters frequently used include:

- meteorological conditions (wind, rain)
- surface roughness (Armbrust et al., 1964)
• soil surface strength (Nickling, 1984)
• soil particle size (Leys and McTainsh, 1996)
• soil aggregation (Chepil, 1950)
• vegetation cover (Findlater et al., 1990; Skidmore and Hagen, 1977); and
• soil moisture.

The early field measurements of McTainsh et al., (1999) showed that different land types had different erodibilities. This was an important step, flagging to the broad-scale modellers that the concept of erodibility varies through space and that surface features were unique to the source areas.

Two of the popular models currently used to define wind erosion are the Wind Erosion Prediction System (WEPS) and the Wind Erosion Assessment Model (WEAM). WEPS was developed for agricultural purposes in the United States (Hagen et al., 1996) using empirical relationships to determine threshold velocities for a range of soil features. Surface crusting is one feature used as parameter in this large, multifaceted model. Surface crust is assigned a number based on its thickness.

In contrast IWEAM (Lu and Shao, 2001) is a physically-based model driven by changes in threshold friction velocity. This model incorporates parameters for cover, soil crusting and moisture. Unlike the moisture and cover parameters which can be estimated via climatic data or satellite imagery, the crusting value currently relies on ground observations. Current use of IWEAM at the Australian continental scale disregards the crust parameter. Although there is acknowledgement of the importance of crusting, there is limited data available to use. The model is run as if the crusts have no effect on the friction velocity (Butler pers comm. 2006).

Two major barriers to the widespread use of crusts as a parameter of erodibility studies are that:

• extensive field-based knowledge is needed to understand their formation, diversity and longevity; and

• crusts can be either biological or physical in origin.

While the first problem is universal, regardless of the type of crust present, and ultimately depends on the experience of the researcher, the descriptions of different
types of crust features usually originate from two different disciplines. This often results in information being published in discipline-specific journals and fosters the notion that biological and physical crusts should be viewed independently of each other.

Some indication in the literature suggests that attempts are being made to include better assessments of crusts. Two recent US studies have classified a range of soil surfaces at the beginning of erodibility projects. Yount et al., (2006) characterised four dominant evaporate crusts, defining their formation and morphological features in the Mojave Desert. Sweeney et al., (2006) developed a highly-portable instrument that offers rapid access to remotes sites, providing a relative measure of erodibility. This approach supports the idea that if more surface types could be identified and quickly analysed, it would allow a greater understanding of the surface.

This chapter explores the first objective of the thesis: to investigate the types and spatial distribution of soil surface types on a claypan of the outer floodplain of the Diamantina River. The Lake Constance claypan will be characterised. First, a rapid and generalised approach is used to describe the geomorphic regions of the claypan relevant to wind erodibility. Then, at a higher resolution of mapping, 1 m x 0.5 m quadrats are examined to better understand the dominance and distribution of surface types. These surface types include four crust types, a stone cover and a grass cover.

### 5.2 Classification of crust forms

The diversity of crust forms results in a great range of terms used to describe them. The most simplistic division is between physical and biological crusts. A myriad of names, descriptions and classification schemes exist. Unless there is a systematic approach to classification, the names become subjective and difficult for non-frequent users to comprehend.

Biological soil crusts (BSC) are made up of diverse communities, and, as a result, their nomenclature is complex. BSCs themselves have been variously labelled ‘cryptogamic’, ‘cryptobiotic’, ‘microbiotic’, ‘microfloral’, ‘microphytic’ and ‘organogenetic’ (Loope and Gifford, 1972; Kleiner and Harper, 1977; Harper and Marble, 1988; West, 1990; Eldridge et al., 1994). Each of these terms suggests a bias
towards one taxonomic group. For example, the terms ‘cryptogamic’, ‘cryptobiotic’, ‘microfloral’ and ‘microphytic’ allude to either plant or animal kingdom associations (Eldridge and Greene, 1994b). This is a misnomer, as BSCs are composed of both non-vascular plants and micro-organisms.

Eldridge and Greene (1994b) propose classifying BSCs into three functional groups based on diagnostic field traits, habitat preference and abiotic relationships:

- **Hypermorphs** (above ground) include the bryophytes (mosses and liverworts). These species offer high erosion protection, but are very sensitive to disturbance.

- **Perimorphs** (at ground) are comprised of the crustose and foliose lichens, and categorised by substantial material both above and below ground.

- **Cryptomorphs** (hidden below ground) are comprised of cyanobacteria, microalgae, fungi and bacteria associations. Their activity is concentrated below ground and contributes to aggregate stability and soil nutrient levels.

Belnap and Lange (2003) offer an alternative classification directed at worldwide comparisons using literature and personal observations. Under this scheme, four crust groups are recognized:

- **Smooth** crusts chiefly consist of cyanobacteria, algae and fungi. These surfaces are extremely flat as a result of cyanobacteria binding loose mineral sediments. Smooth crusts occur in hyper-arid and arid regions, where precipitation is very low, temperatures very high, and soils never freeze. Smooth crusts have a high tolerance of disturbance.

- **Rugose** crusts occur in arid and semiarid regions with lower potential evapotranspiration than areas with smooth crusts. As such, they can contain sparse patches of lichens and mosses but are still dominated by cyanobacteria, algae and fungi.

- **Pinnacled** crusts are again dominated by cyanobacteria, but can support up to 40 percent lichen and moss cover. Characteristic of these crusts are the pedicelled mounds that are formed as the soils are uplifted by frost-heaving and differentially eroded by water. Each pedicel can reach up to 150 mm in height. These crust forms are common in mid-latitude, cool deserts, but are highly sensitive to disturbance.
• **Rolling** crusts occur in yet colder climates, where low potential evapo-transpiration supports growth of lichens and mosses, and/or thick mats of cyanobacteria. The extra binding of the surface sediments via the roots of lichens and mosses creates increased surface cohesion. As such, the effect of frost heaving is not an irregular, pinnacled ‘inselburg’, but rather a rolling, rough surface. Once again, these higher organisms are vulnerable to soil surface disturbance.

Both classification schemes are limited in describing the subtle diversity of the lower-order crust assemblages throughout the world. For example, the deserts of the Kalahari (Dougill and Thomas, 2004; Thomas and Dougill, 2006), Israel (Danin et al., 1998) and Australia (Strong unpubl. data) are dominated chiefly by cryptomorphs, or the smooth crusts. Identifying a lack of discrimination within the smooth crust category, Dougill and Thomas (2004) have proposed a simple dichotomous key based on crust form and morphology. The key uses simple visual clues leading to six basic surface forms: unconsolidated soil/sand; alluvial rich crust; physical crust; and three stages of BSC. This key provides important discrimination between cyanobacterial crusts and should therefore be more widely adopted. All three classification schemes have limited linkages with physical crust taxonomy.

Reporting of the taxonomic or structural compositions of biological crusts is restricted to ecological journals. From an ecological perspective this is the appropriate approach, but from a cross-disciplinary perspective it is restrictive. Baseline papers that propose field classification systems need a wider readership to increase the awareness base. A compendium volume edited by Belnap and Lange (2003) provides much baseline knowledge of biological crusts and will be an influential text in how other researchers categorise the biological crusts.

In contrast, physical crusts have been meticulously classified through investigation of common morphological and physical properties. Valentin and Bresson (1992) provide a very strong basis from which to classify soil crusts. Crusts are classified as either structural, erosion or depositional, with each possessing sub-classes. Descriptions are based on morphology and can be observed in the field with some background knowledge. The authors found that physical crusting consistently followed time and spatial patterns. Such patterns enable the identification of landscape processes such as degradation patterns.
5.3 Soil surface variability on the Lake Constance claypan

At the beginning of a wind erosion study on a claypan, one of the first, informal activities conducted is a visual assessment of the surface to identify geomorphic regions likely to yield sediment. This activity is usually a quick operation, relying on personal experience to rank broad geomorphic regions in terms of perceived erodibility. Often it is this perceived difference in erodibility which determines the placement of traps or areas of experimentation. Measurement of erosion using traps can take place either by using few traps across each of the geomorphic regions for long durations (McTainsh et al., 1999) or by monitoring frequently with many traps for only a short duration (Stout and Zobeck, 1996). Both strategies acknowledge that wind erosion is variable both temporally and spatially, in part because of differences in soil surface characteristics.

The Lake Constance (LC) claypan is a typical outer floodplain claypan of the Diamantina River (see Chapter 2 for a description of this site). The LC claypan abuts a 5 km stretch of the river, and is the largest claypan on either side of the river (Figures 2.1 and 5.1). This pattern of river channels and outer floodplain claypans is common for 600 km of the river’s 900 km length. The boundaries of the 25 km$^2$ LC claypan include the river to the east, dunes to the north and south, and a large, heavily-vegetated flood out region to the west (Figure 5.1).
Figure 5.1. Lake Constance claypan is a mosaic of surface features. Approximately 45 percent of the claypan surface is covered with features which have the highest susceptibility to wind erosion.

Surface features on the claypan vary widely. The satellite image in Figure 5.1 clearly demonstrates this surface heterogeneity. Whiter areas have a higher reflectivity and indicate surfaces devoid of any covering. These areas, commonly known as sealed clay, are smooth and possess little relief or vegetation. It is these features (or the lack thereof) which suggest that these surfaces are the most erodible.

The darker green to black areas associated with the flood out represent vegetated cracking clay soils. Cracking clays are characterised by having:

- a higher relative organic-matter content
- a shrinking and swelling nature
- high aggregation levels; and
- the frequent presence of annual forbs and grasses (Isbell and Hubble, 1983).

These surfaces have a greater resistance to wind erosion due to the vegetation and the highly aggregated nature of the soils.
The lightly-shaded pink areas on the south, northwest and northern boundaries of the marked zone have *gibber* surfaces. Gibbers, consisting of gravels varying in size from 5 to 50 mm in diameter, are regarded as being a residual sediment layer leftover from the erosion of laterite surfaces. Gibber surface cover varies from sporadic to complete pavement. Traditionally, these surfaces are viewed as protecting the soil surface from wind erosion by providing a physical barrier on the soil surface.

*Streamlines* occur on the claypan, draining the claypan surface following both rainfall and flooding. Streamlines usually form incisions with a greater depth than width. As a result, the stream morphology is unlikely to be subjected to forces of wind erosion.

### 5.3.1 Broad scale mapping of geomorphic regions

The initial assessment of erodible regions on the claypan is a critical step in identifying the soil surface variability. This is usually based on intuition and brief drive/walk throughs, sometimes aided with photographic imagery. The four geomorphic regions inferred from Figure 5.1 (sealed clay, cracking clay, gibber and streamlines) represent one such approach. To test spatial representation of such an approach, a broad scale transect survey was conducted of the LC claypan. Thirty three transects spaced 150 m apart were driven in a NE to SW direction across the claypan with a quad motorcycle. GPS and odometer readings were taken at each change in surface features, categorising the surfaces into sealed clay, cracking clay, gibber and streamlines. The GPS reading provided the position of change and the odometer gave the spatial extent of the surface feature. Boundaries were delineated by remote sensing. The percent coverage of each surface class was calculated for each transect and a final approximation of claypan coverage was estimated by pooling the transect values.

Forty-two percent of the distance traversed was classified as sealed clay. Cracking clay comprised 22 percent, gibber 17 percent and streamlines 19 percent (Figure 5.2). In effect, nearly half of the claypan is comprised of surfaces that are thought to have the highest rates of erodibility. Distribution of the geomorphic groupings across the claypan appears to follow little pattern (Figure 5.1). The streamlines are concentrated on the northern and eastern sector of the pan, draining runoff back the Diamantina River. Cracking clay appears associated with the flood out to the west and
infrequently along side streamlines. The sealed clay and gibber surfaces randomly appear across the pan.

Figure 5.2 Categorising the Lake Constance claypan into broad erodible regions identifies that the surface most subject to wind erosion, sealed clay, dominates the surface.
Figure 5.3. Spatial heterogeneity of erodible regions indicated on the LandSat image of Lake Constance claypan. Changes in the broad surface features were identified by soil survey and boundaries delineated by remote sensing. Different symbols represent various surface conditions.

The spatial heterogeneity of the surface features described for the LC pan is comparable to other arid regions (Thomas and Dougill, 2006). The identified spatial heterogeneity is suggested to be vital for the functioning of a landscape, particularly from an ecological perspective (Dougill and Thomas, 2004). Models developed to describe ecosystem patterning of arid lands, such as the Landscape Function Analysis (Tongway and Ludwig, 1994), often focus on macro components, such as vegetation, and the impact they have on nutrient redistribution. Vegetation canopies act as nutrient sources by elevating organic matter contribution to the soil and providing a trapping mechanism for transported sediments (Dean et al., 1999; Tongway and Ludwig, 1994). Such concentrations of nutrients and organic matter around shrubs have been described as ‘islands of fertility’ (Schlesinger et al., 1990).
Biological crusts may contribute to these ‘islands of fertility’ by increasing the nutrient and organic content of the surface soils in an otherwise nutrient-poor environment (Dougill and Thomas 2004). Many members of the biological community are known to fix atmospheric nitrogen (Belnap et al., 1994) and alter nutrients levels in the soil (Bowker et al., 2006). Some have been noted to trap finer sediments, such as silt, thus altering the structure and nutrient status of the soil (Danin and Ganor, 1997; Belnap, 2003). This provides evidence that the biological crusts could be acting as fertility islands. But if this is the case, why are they not identified during field-site setup surveys?

The broad scale at which geomorphic regions are mapped will commonly miss micro elements, such as the distribution of physical and biological crusts, micro topography and sandy deposits induced by vegetation. It is at this finer scale that erodibility is controlled. The four geomorphic regions (sealed clay, cracking clay, gibber and streamline) used so far to describe a large area of the LC claypan are a convenient way of identifying potentially erodible areas, but in reality much detail is missed. If erodibility is to be better understood, a higher resolution assessment of the variation in surface types is required.

An example of the subtleness of soil surface conditions can be seen in Figure 5.4a which has a cyanobacteria crust in the foreground and a structural crust surrounding it. These surfaces would have been classed as a sealed clay during the transect survey. This is understandable as at a coarse scale they look similar, with perhaps slightly greater surface roughness in the cyanobacteria crust and more surface cracking in the structural crust, but there is an obvious surface colour (reflectivity) difference between them. Subtle differences such as these are simply overlooked when broad, geomorphic regions are used to classify soil surfaces. Figure 5.4b highlights the effect of such subtle differences. The lighter, white colour areas are a close up of the cyanobacteria crusts in Figure 5.4a; the patches of darker red are a sand deposit on top. The increased surface roughness of the cyanobacteria site has captured saltation sands which were moving from the background to foreground. On closer inspection of Figure 5.4a it can be appreciated how much saltation sand has been trapped. This is a considerable deposition of sediment, destined to become saltation sediment again once a stronger wind occurs.
Figure 5.4. Wind erosion event blowing saltation sediments from background to foreground. a) cyanobacteria crust in foreground surrounded by structural physical crust, dune on horizon. b) close up of saltation sands deposited on cyanobacteria crust in foreground.

Such oversights are common when grouping large regions, as there is huge variety between the surface features. Some of the common variations include (see also Figure 5.5):

- the density of gibber
- the range of vegetation cover and surface roughness on cracking clays
- the range of surface types encompassed by sealed clay, including both physical and biological crusts
- the structural, depositional and erosional crusts which comprise physical crusts
- descriptions of physical crusts, such as sealed fluvial clay, wind sheeted, clay curls, smooth sealed clay, vesicular crust, cracking sealed clay and polygenic clay; and
- Cyanobacteria-dominated BSCs found on sand sheets and coppice dunes, with and without associations to vegetation
Gibber surfaces – three densities

Cracking Clay – three phases of development

Erosion Crust
Figure 5.5. Variety of surface forms within each of the surface classes. The geomorphic region sealed clay, varies greatly, encompassing both physical and biological crusts.
5.3.2 High-resolution mapping of surface type—stratified sampling

Acknowledging that classifying the claypan into four geomorphic regions underestimated the soil surface variability led to reclassifying the claypan surface using an increased number of categories and a stratified sampling strategy. One hundred and fifty-seven sites across the claypan were visually assessed for both the abundance and spatial heterogeneity of crusts, plants and other surface characteristics. The sample locations were randomly selected using the geo-statistical layout outlined in Chappell et al., (2003b) and Chapter 3.3.2. Each of the 157 sites was classified according to its dominant surface type. Surface types included gibber stones, grassed cracking clays, depositional crusts, structural crusts and cyanobacteria crusts. Soil samples were also collected at each site and analysed for coarse particle-size characteristics and electrical conductivity (also outlined in chapter 3.3.2).

Structural crusts were the most abundant surface type, comprising 46.5 percent of the samples. Grassed cracking clay comprised 22.3 percent of the sites tested, cyanobacteria crusts 13.4 percent, gibber stones 10.8 percent and depositional crusts the remaining 7 percent (Table 5.1). The percentage surface cover of these morphological groupings is consistent with the higher-resolution sampling density presented in Figure 5.2.

The patterning suggests that some surface types correspond to the underlying soil properties. This can be determined either:

- visually, with maps of the soil property overlaid with the surface types identified at the 157 sites (Figure 5.6, Figure 5.7); or
- statistically, using ANOVAs to identify statistical differences and rankings of results (Table 5.1).

**Cracking clay** visually appears to align with areas of the highest clay content, lowest silt, and fine sand, but areas close to the dune had moderate coarse sand inclusions (Figure 5.6). Statistical significance at the 95 percent confidence confirmed this visual ranking, grouping cracking clay with clay content but suggesting that coarse sand was not specifically aligned with cracking clays (Table 5.1).
Table 5.1. The total abundance of five morphological groups across the 157 sampling sites of the LC claypan showing the frequency and variability of soil type, vegetation cover and soil conductivity occurring on each of the surface types.

<table>
<thead>
<tr>
<th>Surface Type</th>
<th>Abundance</th>
<th>Clay %</th>
<th>Silt %</th>
<th>Fine %</th>
<th>Sand %</th>
<th>Coarse %</th>
<th>Sand %</th>
<th>Vege Cover %</th>
<th>EC 1:5 um/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cracking Clay (n = 35)</td>
<td>22.3</td>
<td>40.20</td>
<td>a 1.69</td>
<td>23.6</td>
<td>a 1.06</td>
<td>33.25</td>
<td>a 1.68</td>
<td>2.79</td>
<td>0.57</td>
</tr>
<tr>
<td>Cyanobacteria (n = 21)</td>
<td>13.4</td>
<td>31.71</td>
<td>c 1.83</td>
<td>25.06</td>
<td>ab 1.40</td>
<td>39.52</td>
<td>b 2.56</td>
<td>3.19</td>
<td>1.23</td>
</tr>
<tr>
<td>Depositional Crust (n = 11)</td>
<td>7</td>
<td>41.12</td>
<td>ab 1.44</td>
<td>26.16</td>
<td>ab 1.91</td>
<td>30.50</td>
<td>a 2.10</td>
<td>2.23</td>
<td>0.96</td>
</tr>
<tr>
<td>Gibber (n = 17)</td>
<td>10.8</td>
<td>32.83</td>
<td>c 1.93</td>
<td>22.72</td>
<td>a 1.52</td>
<td>32.65</td>
<td>a 1.62</td>
<td>7.41</td>
<td>2.06</td>
</tr>
<tr>
<td>Structural Crust (n = 73)</td>
<td>46.5</td>
<td>35.64</td>
<td>bc 0.75</td>
<td>28.94</td>
<td>b 0.66</td>
<td>34.32</td>
<td>a 0.86</td>
<td>1.05</td>
<td>0.18</td>
</tr>
<tr>
<td>F test significant</td>
<td>P = 0.0001</td>
<td>P = 0.0001</td>
<td>P = 0.028</td>
<td>P = 0.0001</td>
<td>P = 0.0001</td>
<td>P = 0.0001</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

n = number of samples; x = mean; se = standard error; P = 0.0… = the level to which the ANOVA is significant; italicised letter beside the mean represents groupings within the data sets that have statistical similarities.
**Cyanobacteria** crusts visually appear to align with areas of highest fine sand content (20 – 200 µm), lowest clay content and moderate levels of silt and coarse sand (Figure 5.6). Statistical significance at the 95 percent confidence confirmed this visual ranking, isolating cyanobacteria crust in its own group with respect to fine sand percent. The other particle-size classes were not specifically aligned with cyanobacteria crusts (Table 5.1).

**Depositional** crusts visually appear to align with areas of highest clay content (< 2 µm), lowest sand fractions, but moderate levels of silt (Figure 5.6). Depositional crusts have the statistically highest levels of clay content, being grouped together with the cracking clay surface type. The other particle-size classes were not specifically aligned with depositional crusts (Table 5.1).

**Gibber** surfaces visually appear to align with areas of highest coarse sand content (> 200 µm), lowest clay and silt fractions, but moderate levels of fine sand (Figure 5.6). Gibber surfaces have the statistically highest levels of coarse sand content compared to the other four surface types (Table 5.1). The increased surface roughness created by the gravel surface produces a greater storage potential.

**Structural** crusts visually appear to align with areas of highest silt content (2-20 µm), lowest coarse sand fraction, but moderate levels of clay and fine sand (Figure 5.6). Structural crusts have the statistically highest level of silt content compared to the other four surface types (Table 5.1).
Figure 5.6 a-d. Spatial distribution of 5 different geomorphic groupings across four textural properties; a) clay < 2 µm, b) silt 2 – 20 µm, c) fine sand 20 – 200 µm, and d) coarse sand > 200 µm across Lake Constance claypan.
Cracking clay surface types visually align with the areas of highest vegetation cover. (Figure 5.7a). These surface types are statistically different from the other types (Table 5.1). Cracking clays are free draining, have high CEC and high organic carbon levels compared to surrounding soils (Wilson et al., 1990), and are therefore capable of supporting a wide range of vegetation. Cyanobacterial crusts were statistically found in association with vegetation, but visually were a little difficult to distinguish. The high vegetation levels found with these surface types is also a function of electrical conductivity (EC). Cracking clay and cyanobacteria surface types had the lowest readings of EC (Figure 5.7b). The nature of the soil profiles at the cracking clay and cyanobacteria surface types—deep cracking clays and a high proportion of coarse sands respectively—would encourage low salt contents.

The depositional and structural crusted surfaces, along with the gibber surfaces, were statistically grouped together as having the lowest vegetation contents (Table 5.1). This aligns with the highest EC at these three surface types (Figure 5.7b). Not only does salt inhibit the growth of vegetation, but it is instrumental in the formation of physical crusts, particularly structural crusts (Valentin and Bresson (1992).

Figure 5.7 a-b. Spatial distribution of 5 different geomorphic groupings compared to the distribution of vegetation cover and electrical conductivity across Lake Constance claypan.
5.4 Spatial patterns of sediment transport

In an attempt to identify relationships between sediment flux and surface types, the surface types were overlaid on sediment transport maps. Nearest-neighbour interpretation between 40 sediment collections were used to generate sediment maps across the LC claypan for four wind erosion events. Sediment traps were positioned at a height of 7 cm, collecting saltation sediments. It is acknowledged that this interpretation tool is a less powerful algorithm compared to the krigging technique of Chappell et al., (2003b). Kriging is a group of geostatistical techniques to interpolate the value $Z(x_0)$ of a random field $Z(x)$ at an unobserved location $x_0$ from observations $z_i = Z(x_i), i = 1, \ldots, n$ of the random field at nearby locations $x_1, \ldots, x_n$. Kriging computes the best linear unbiased estimator $\hat{Z}(x_0)$ of $Z(x_0)$ based on a stochastic model of the spatial dependence quantified and in the case of Chappell et al., (2003b) by the variogram $\gamma(x,y)$ and the covariance function $c(x,y)$ of the random field. In comparison the nearest-neighbour algorithm used MapInfo Vertical Mapper is a simple method of multivariate interpolation in two dimensions. The nearest neighbor algorithm simply selects the value of the nearest point, and does not consider the values of other neighboring points at all. While this algorithm is very simple it provides suitable measure at this spatial scale.

Visual assessment of the patterns between sediment transport maps and the distribution of surface types suggested that it is the cyanobacteria crusts and gibber surfaces which are associated with the higher sediment flux (Figure 5.8a-d). The cracking clay surface types occur in the regions of lowest sediment flux, while there is a variable response for the structural and depositional crusts. Initially, it was surprising that the structural crusts did not align with high sediment flux, as this surface type dominates the claypan and was perceived at the outset of the study to be erodible.
Chappell et al., (2003b), working on the LC claypan, identified that that the spatial variation in erodibility was greater than the spatial scale of the transport. Erodibility in this case was inferred from the punctual krigging models which the authors used. They suggested that to accurately measure the erodibility of this site would require considerably more sediment traps than the 40 used. Logistically, this is not possible. Instead, Chappell et al., (2003b) produced sediment transport maps for eight events across the LC claypan by using the punctual krigging technique every 100 m. These maps highlighted that the spatial distribution of
sediment collection indeed varied between the events. They did not, however, attempt to make any associations with the surface types.

Perhaps the major limitation to inferring sediment flux from the surface type on which the sediment trap is positioned is that wind erosion is multi-directional. Sediment could therefore have travelled from any direction over distances of a few centimetres to kilometres. This means the position of the sediment trap may not specifically reflect the erodibility of the surface type in which it was positioned. This can occur if, for example:

• the sediment trap is downwind of an erodible surface
• the surface conditions of the trap position are conducive to sediment catchment; or
• the sediment trap is positioned in a sediment source area.

One example of this variability has already been given in Figure 5.4. The red saltation sands trapped in the cyanobacteria crust clearly demonstrate the capacity of the sediment to be transported great distances. These sediments were observed to have travelled over 500 m from their source area. They travelled across possibly ten different surface types and passed up to eight sediment traps. Had these sediment traps been active, this event would have modified the spatial patterning of the sediment transport maps, possibly elevating the perception of structural crusts as being source areas.

Therefore, while Chappell et al., (2003b) were able to infer that the spatial pattern of erodibility was greater than the spatial scale of the transport, and this thesis was able to show general trends of surface-type distributions with respect to sediment transport maps, there is the need to improve linkages between measurement of erodibility and sediment transport. This is not a simple task; wind erosion researchers have been attempting such activities for many years. Empirical studies of different features known to affect soil erodibility, such as aggregation (Chepil, 1951; Larney et al., 1995; Leys et al., 1996), moisture (Shao et al., 1996) and vegetation cover (Findlater et al., 1990; Armbrust and Bilbro, 1997) have been developed to help understand erodibility. Broad-scale numerical models which incorporate generalised input attributes (Lu and Shao, 2001) help identify some of the controlling factors of wind erosion, however, there is a fundamental need to characterise the erodibility of a range of surface types. Chapter 6 will achieve this by taking the novel approach of characterising four surface types with multiple erodibility measures. The measurement results will be combined to produce an erodibility map of the LC claypan.
5.5 **Summary**

This chapter has shown that the LC claypan is composed of multiple surface types, of which crusts dominate. The spatial patterning of these crusts varies at sub metre scales with the crust compositions representing a range of physical and biological processes. Structural crusts dominate the claypan, with other surfaces including biological crusts, cracking clays, gibber and depositional crusts. Structural crusts are seen to provide much of the sediment which is entrained as dust. This view, however, is based on broad-scale measurement of wind erosion. When the spatial patterning of surface types is related to sediment transport it is shown that this is not the case. The cyanobacteria crusts and gibber surfaces appear to align to the highest sediment flux sites. Relating the spatial patterning of surface types to sediment flux is fraught with danger as the positions of the traps do not necessarily reflect the erodibility of the surface type, and the understanding of the factors that control the erodibility are limited.
Chapter 6. Measures of Relative Erodibility of Different Crust Forms

6.1 Introduction

Erodibility is defined as the susceptibility of a soil surface to erosion, and in this thesis to wind erosion only. While this definition may appear simple, the actualities are very complicated. First, there is the potential to confuse the concept of erodibility with the different measures of erodibility; which include erodibility output measures such as sediment flux and measures of soil characteristics that influence erodibility. Second, these soil characteristics have a variety of interactions both within the soil and on its surface the sum of which present as the erodibility. In addition, all of these properties change through space and time. Therefore a geomorphic feature such as the LC claypan does not have a single erodibility, but rather a complex mixture of erodibilities.

There is little agreement in the literature as to what parameters best describe the erodibility of a soil. Commonly, soil characteristics are given, such as aggregation, soil texture and soil binding agents (Geeves and Leys, 1999). Depending on the land use (agricultural or rangeland) surface features such as crusting may be considered. The concept of erodibility therefore is often confused and in attempt to breakdown this confusion I propose that the terminology be revised as follows (text relates to Figure 6.1)

- Erodibility Concept: Erodibility is the susceptibility of a soil to erosion. There is erodibility inherent to the soil – soil erodibility ($E_{soil}$) and to the soil surface – surface erodibility ($E_{surface}$) which interact with each other to produce overall erodibility.

- Erodibility Characteristics: Both the soil and the soil surface have inherent characteristics which contribute to the overall erodibility. Therefore erodibility characteristics should be viewed AND reported as both soil erodibility characteristics ($E_{soil}$) and surface erodibility characteristics ($E_{surface}$).

- Erodibility Output Measures: A number of measurement instruments are used to quantify the amount of sediment lost from a site during erosion, for example, wind tunnels, sediment samplers and even wind erosion event frequencies. The units of their measurement form the erodibility output measures, e.g sediment flux, sediment concentration and dust storm frequency. The erodibility output measures are ‘blunt’ tools
(usually a number) which whilst quantifying the overall erodibility do not and *can not* partition which of the erodibility characteristics are controlling the current erodibility status.

Figure 6.1 Conceptual diagram outlining the key components associated with erodibility; concept, characteristics and measures. Also shown are the erodibility characteristics and erodibility measures used in this thesis.

The $E_{\text{surface}}$ characteristics are generally poorly understood and therefore under represented within the erodibility literature. The geomorphic focus of this thesis and the rangeland setting means that surface features need to be well represented. Soil crusts are a common feature throughout the arid rangelands, and, as shown in Chapter 5, dominate the LC claypan. A range of $E_{\text{surface}}$ characteristics can alter the erodibility of a soil crust. These are generally
those properties of the crust that control the resistance of a surface to fracture. One frequently-measured property is ‘crust strength’, showing a crust’s ability to resist saltation impact and thereby reduce soil erodibility. In reality, however, crust strength is, in part at least, a factor of a number of other attributes, including spatial uniformity, particle size composition and crust thickness.

Different crust types display different crust strengths. The underlying properties that contribute to crust strength vary between crusts. In the case of biological crusts, McKenna-Neuman and colleagues (McKenna Neuman et al., 1996; McKenna Neuman and Maxwell, 1999; McKenna Neuman and Maxwell, 2002; McKenna Neuman et al., 2005) identified that crust strength could be attributed to the growth habits of different crust species. These authors meticulously grew monocultures of nine different species, ranging from algae to mosses, for wind tunnel simulations. Algae and cyanobacteria, which grew through the soil surface, offered less resistance to saltation impact compared to mosses, which have above-soil structures. The cyanobacteria provided greater strength than the algae due to its aggressive sheath growth and polysaccharide production. On the other hand, for physical crusts it appears that those with unimodal sediment size have a lower strength than those with multiple sized sediments (Rice and McEwan 2001), in this case emphasising the importance of particle size to crust strength.

In addition to crust surface strength, the energy-delivering saltation particles are also a key component of soil surface rupture, and therefore erodibility (Rice et al., 1999). Saltation particles deliver a range of energies to the soil surface because of different particle sizes, variable particle trajectories and variable wind strength. When these variables are combined and plotted, the energies delivered by a saltation cloud represent a skewed distribution. The finer end corresponds to the high-energy tail of the distribution which consists of fewer, but more energetic, particles which have a greater erosive potential. The spatial strengths of the soil surface will also produce a skewed distribution, the finer end in this case representing the weak surface strengths. Although more infrequent, the areas of weaker surface strength produce the areas most vulnerable to saltation impact. The few high-energy saltation particles impact on the few regions of weaker soil strength (Rice et al., 1999). Once a crust has been penetrated, underlying sediments become available for entrainment and areas of reduced strength increase. In effect, the interaction of crust strength and saltation energy determines not only the erodibility of crust surfaces, but also the acceleration of this process and further breakdown of the crust.
Crust thickness is critical in determining the time it takes the crust to be penetrated by saltating particles: thinner crusts require less saltation impact before penetration occurs (Rice et al., 1997). Saltating particles have traditionally been considered to only have sufficient energy to disrupt inter-particle bonding in weak to medium-strength crusts or aggregates (Rice et al., 1997). Wind tunnel simulations on physical crusts, however, have shown that the presence of any weakness in a crust allows penetration and a similar acceleration of crust destruction (Rice et al., 1997). In the case of Rice et al., (1997) the presence of fine fractures was sufficient. Once compromised along fracture lines, scouring occurred followed by undermining of the crust, ultimately resulting in large pieces of crust being removed. A similar scouring of sediment from under biological crusts was detected in laboratory wind tunnel simulations (McKenna Nueman et al., 1996). This scouring often produces large, unsupported crust pieces that ‘flap in the breeze’ until the hinge point suffers fatigue and fracture occurs (McKenna Neuman and Maxwell 1999). These studies have shown that under the impact of saltation bombardment, the number of fine fractures is just as important as the thickness of the crust.

Wind tunnel studies in the field support the notion that saltation impact is the primary mechanism for biological crust destruction (Belnap and Gillette, 1998). Despite this, the biological soil crusts are consistently found to be resilient to saltation impact compared to other crust forms. Erodibility assessments of surfaces with and without biological crusts, surfaces with chemically killed biological crusts, and crusts of known time-since-disturbance or disturbance intensity (Williams et al., 1995; Belnap and Gillette, 1997; Belnap and Gillette, 1998; Leys and Eldridge, 1998) have all demonstrated that an undisturbed biological crust requires a higher friction velocity to initiate entrainment. Possible explanations for this phenomenon include:

• physical modification of the surface roughness by the crust itself
• filamentous growth through the soil profile, binding the soil particles together (Belnap and Gillette, 1998)
• production of polysaccharides that enhance aggregation (Eldridge and Leys, 2003); and
• the inclusion of fine sediments trapped by the surface roughness, creating a tightly-packed soil matrix (Danin and Ganor, 1997).

Estimates of the $E_{surface}$ characteristics need to account for a complex set of characteristics relating to both the soil’s properties and its surface features. Such characteristics might
include soil properties such as aggregation, moisture, organic-matter content and the presence of a crust and its type. Despite the conventional view that these characteristics interact to affect a soil’s erodibility, they are often measured individually. As a result, empirical relationships are constructed between individual soil characteristics and rates of wind erosion that do not accurately reflect the interdependent nature of erodibility. This also means that no single, reliable measure of soil erodibility can be identified.

Crust formation involves many interacting processes. For this reason, focusing on soil surfaces that feature soil crusts provides an opportunity for a more comprehensive approach to the study of erodibility. This chapter addresses the third objective of the thesis: to determine the erodibility of different soil surface types on a claypan.

6.1.1 Research approach

Previous assessments of the erodibility of soil crusts have generally concentrated on the impacts that crusts have on wind erosion processes by using only one or two measurement techniques (see Chapter 1). This study has taken the novel approach of incorporating multiple methods of assessment in an attempt to find a more reliable measure of erodibility, at least for crusts. As alluded to above (section 6.1), few studies have used multiple measurement techniques to investigate the erodibility of individual crust units in the field. Erodibility outcome measurements were initially made with the MWT. Two measures were generated using this instrument, sediment flux and saltation induced sediment flux. In an attempt to understand the erodibility outcome measurements a wind erosion model was used to make an estimate of erodibility, providing in effect a therotical baseline of erodibility. The erodibility characteristics of both the soil and surface were then investigated in attempt to identify which ones were contributing to the overall erodibility.

The erodibility characteristics used to explore the overall erodibility include:

- $E_{\text{soil characteristics}}$;
  - high-resolution particle-sizing

- $E_{\text{surface characteristics}}$;
  - soil strength
  - biological characterisation along with spatial heterogeneity
  - loose, erodible-material assessment; and
• abrasion resistance.

Four field sites (dune, sand sheet, washout and sealed clay) were selected for the measurements. The chosen sites represent surfaces commonly found on the LC claypan and neighbouring dune, and each type is known to contribute to natural wind erosion on the claypan. The four field sites represent three different parent soils, each arising from a different formation process, resulting in four different surface morphologies. The results of the modelling and empirical analyses were then compared and reviewed in an attempt to:

• better understand the interactive forces determining erodibility and their relationship to the spatial heterogeneity of wind erosion; and

• produce a more realistic measure of erodibility.

6.2 Erodibility Output measures: sediment flux

Erodibility in the form of sediment flux is commonly measured using wind tunnel simulations. The micro wind tunnel (MWT), described in Chapter 4, and was used in two ways as an erodibility outcome measurement instrument on the four soil surface types in situ:

• First, the sediment flux released from the soil surface was calculated by allowing only wind down the tunnel, relying on any naturally-available, loose, erodible material to act as a saltation source.

• Second, the saltation induced sediment flux of the soil surface was determined by adding saltation sediments to the tunnel runs.

6.2.1 Sediment flux

With both modes of operation, five tunnel velocities were replicated three times at each of the four sites (dune, sand sheet, washout and sealed clay). Wind-removed sediment was collected on 125 mm-diameter glass-fibre filter paper with 0.1 µm pores, and weighed. Sediment flux (Q) (g/m/s) with no added saltation material was calculated as:

\[ Q = \frac{\text{mass}}{[0.01m^2 \times 60s]} \]  

[6.1]

where mass is the weight (g) of sediment collected on the filter paper.
By simulating five wind speeds on all surfaces a trend line indicating how sediment flux changes with wind speed can be determined. Comparing between the surfaces requires a standard wind speed to be selected and used as the default comparison value. The chosen wind speed to do this was $U^3 = 3000 \text{ m}^3/\text{s}$ because it is a common entrainment causing wind speed seen in the field. References to $U^3 = 3000 \text{ m}^3/\text{s}$ from here on indicate that comparison between the four surfaces are being made and values are determined from the trends determined from the multiple wind speeds determined with the MWT.

The results indicated that the dune was highly erodible. On average, the dune sediment flux ($Q$) was twice that found across the three claypan sites (sand sheet, washout and sealed clay) (Table 6.1). Across the claypan sites, the sediment flux varied considerably, with the sand sheet having a higher sediment flux than the dune, the washout four times less than the dune, and the sealed clay ten times less than the dune (Table 6.1). This measured sediment flux result differs from the WEAM modelled erodibilities in that one claypan site is ranked higher than the dune surface.

Comparing the modelled sediment flux to the measured sediment flux also highlights fundamental assumptions made within the WEAM parametisation. The WEAM model is developed around a theoretical framework chiefly for agricultural soils. Although the model does include a parameter for crusting, its value was set to the arbitrary ‘1’ value. Little work has actually investigated how the crusting parameter should vary according to different crust types and as such it appears that the WEAM model can not simulate the complexity of interstitial forces found in a crusted surface. This has resulted in the modelled sediment flux for the dune far exceeding the measured values.

<table>
<thead>
<tr>
<th>Measured Q (g/m/s)</th>
<th>Dune</th>
<th>Claypan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment Flux</td>
<td>0.02</td>
<td>0.012</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sand Sheet</th>
<th>Washout</th>
<th>Sealed Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03</td>
<td>0.005</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Sediment flux increased linearly with wind speed$^3$ for all sites (Figure 6.2). This linear increase in $U^3$ was expected and conforms to the work of Shao et al., 1993a.
Figure 6.2. Response of sediment flux (Q) with increasing wind speed (m$^3$/s) of four soil surfaces.

However testing these linear sediment flux expressions for parallelism, coincidence of the slopes and intercepts (Table 6.2) suggested that it was only the sand sheet site which was significantly different from the others. Only one of the linear expressions significantly different was unexpected as visually the expressions appear to fall out into two groupings:

1. The dune and sand sheet
2. The washout and sealed clay sites

These surfaces have intercepts that were not significantly greater than zero, which is consistent in process terms in that a minimum wind speed is required before entrainment can occur.

Table 6.2. Table of statistical significance for saltation fluxes ($P > 0.05$). Surfaces without * indicate a non significant result.

<table>
<thead>
<tr>
<th></th>
<th>Intercept</th>
<th>df</th>
<th>$R^2$</th>
<th>$P$ value</th>
<th>Significant</th>
<th>Similarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand Sheet</td>
<td>-0.0002</td>
<td>3</td>
<td>0.91</td>
<td>0.011</td>
<td>*</td>
<td>a</td>
</tr>
<tr>
<td>Dune</td>
<td>-0.0002</td>
<td>3</td>
<td>0.65</td>
<td>0.101</td>
<td></td>
<td>a</td>
</tr>
<tr>
<td>Washout</td>
<td>+0.0022</td>
<td>3</td>
<td>0.48</td>
<td>0.196</td>
<td>b</td>
<td></td>
</tr>
<tr>
<td>Sealed clay</td>
<td>+0.0002</td>
<td>3</td>
<td>0.59</td>
<td>0.128</td>
<td>b</td>
<td></td>
</tr>
</tbody>
</table>
6.2.2 Saltation induced sediment flux

Saltation induced sediment flux ($Q_{SI}$) (g/m/s) is a measure of erodibility, determined with the MWT, to identify the resistance of a soil surface to saltation impact. Surface breakdown can be accelerated through the effect of saltation bombardment. Not all surfaces have a high level of local, loose saltation material; instead, it is blown in from upwind sources. As such, the sediment flux measure does not provide a consistent measure of saltation impact because each surface had variable rates of natural, loose saltation material. In the second set of experiments, the same protocol was followed as for the first experiment, but a given amount of saltation sand (30 g) was added to each of the five tunnel velocities for each run. The filter papers collected after each run had a mixture of both the added saltation sediments and the eroded sediment from the soil. After weighing, ten percent of the added mass of the abrader sand was subtracted from the total collected mass to determine the abrasion sediment flux rate ($Q_{SI}$). As outlined in Chapter 5, the sediment collection trap of the MWT represents only 10 percent of the cross-sectional area of the tunnel. Therefore, of the 30 g of saltation sediments added at the beginning of the tunnel, 3 g should be collected on the filter paper. Saltation induced sediment flux ($Q_{SI}$) (g/m/s) was calculated as:

$$Q_{SI} = \frac{[mass - 3g]}{[0.01m^2 \times 60s]} \quad [6.2]$$

Comparison between the four surface types were made at wind speed $U^3 = 3000$ m$^3$/s. Characterising the saltation induced sediment flux of the soil surfaces at this speed indicated that the dune was the most erodible, however the average saltation induced sediment flux ($Q_{SI}$) of the dune was only 1.5 times greater than the claypan average (Table 6.3). The variation between the three claypan sites was lower than that identified with the first set of sediment flux runs (compare Table 6.1). The sand sheet was closer to the dune fluxes than the washout and sealed clay (Table 6.3); however the greatest increase in sediment flux occurred with the washout and sealed clay. These surfaces are naturally low in loose saltation material, and as a result, the introduction of saltation material to these surfaces via the air stream produced the greatest impact. The sealed clay surface experienced an increase in sediment flux by a factor of nearly 20 from $Q$ to $Q_{SI}$ with the addition of saltation, whereas the washout increased by a factor of 7.6, sand sheet by 1.8 and the dune by only 0.3. Adding saltation material to the MWT simulates the natural process in which saltation material is sourced.
upwind. The finding that the washout and sealed clay responded the greatest to the addition of saltation suggests that their erodibility is strongly tied to this mechanism.

Table 6.3. Saltation induced sediment flux (g/m/s) of the four soil surfaces using the MWT. $Q_{SI}$ is the sediment flux with saltation sediment added to the tunnel runs.

<table>
<thead>
<tr>
<th>Measured $Q_{SI}$ (g/m/s)</th>
<th>Dune</th>
<th>Claypan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saltation induced sediment flux</td>
<td>0.061</td>
<td>0.044</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sand Sheet</th>
<th>Washout</th>
<th>Sealed Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.056</td>
<td>0.038</td>
<td>0.039</td>
</tr>
</tbody>
</table>

Using regression analysis, it was found that the saltation induced sediment flux values increased linearly with wind speed\(^3\) (Figure 6.3). The regressions were tested for parallelism and coincidence of the slopes and intercepts for $Q_{SI}$. Data indicated that there were significant differences between sediment fluxes for some surfaces. The sand sheet was significantly different to all other sites. The dune and washout were similar to each other, as were the washout and sealed clay (Table 6.4). This principally reflects sediment availability in the form of loose erodible material (LEM). The addition of saltation material increases overall rates of sediment flux, indicating that the surfaces were indeed abrading. These results confirm that LEM is a critical component for crust abrasion. LEM is often a common feature of both crusted and non-crusted surfaces, frequently created by disturbance (Bagnold, 1941). Field measurements of wind erosion conducted by Hupy (2004) demonstrated that upwind LEM sources directly impact on the downwind erodibility, the LEM ‘storing zones’ providing a source of abrasion material for downwind sites.
There were subtle differences between the modelled sediment flux and the measured sediment flux for the four field sites. Based solely on particle-size, WEAM separated the dune and the three claypan sites by a factor of 5, yet measurements with the MWT identified two groupings—the dune and sand sheet—as higher sediment emitters, and the washout and sealed clay as lower emitters. The MWT measured sediment flux that was responding to a range of properties. The wind characteristics measured with the wind tunnel suggested that surface conditions could have contributed to the variation in fluxes. As the wind tunnel applied a standard wind, any differences in the friction velocity ($u_*$) and surface roughness ($z_o$) values were associated with the surface properties. The momentum integral method (as described in Chapter 4.5.2) was used to determine both the friction velocities and the surface roughness of each of the MWT runs. The surface roughness ($z_o$), was highest on the sand
sheet site (Table 6.5). This can be attributed to presence of cyanobacteria crusts and vegetation. The surface roughness of the dune was deceptive; despite its perceived rough surface, it was calculated to have the lowest surface roughness. This result is a factor of scale, as there was little ‘micro-roughness’ in the dune surface; rather, it had smooth undulations that were measured at scales of metres. In comparison, the sand sheet, washout and sealed clay had changes in surface topography within the one metre working length of the tunnel.

Table 6.5. Measured and derived soil and wind characteristics for all four crust forms. U(ave) is the average wind speed measured in the tunnel at 0.025 m across all wind treatments, $u^*$ is the friction velocity, $z_o$ is the aerodynamic roughness length.

<table>
<thead>
<tr>
<th>Crust/Treatment</th>
<th>U (ave) (m/s)</th>
<th>$u^*$ (m/s)</th>
<th>$z_o$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dune</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q$</td>
<td>11.1053</td>
<td>0.4577</td>
<td>0.0156</td>
</tr>
<tr>
<td>$Q_{SD}$</td>
<td>10.7471</td>
<td>0.4343</td>
<td>0.0149</td>
</tr>
<tr>
<td>Sand Sheet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q$</td>
<td>13.4992</td>
<td>0.6851</td>
<td>0.0575</td>
</tr>
<tr>
<td>$Q_{SD}$</td>
<td>11.2581</td>
<td>0.5144</td>
<td>0.0461</td>
</tr>
<tr>
<td>Washout</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q$</td>
<td>13.2646</td>
<td>0.5985</td>
<td>0.0195</td>
</tr>
<tr>
<td>$Q_{SD}$</td>
<td>11.9179</td>
<td>0.5106</td>
<td>0.0171</td>
</tr>
<tr>
<td>Claypan</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q$</td>
<td>13.7806</td>
<td>0.6321</td>
<td>0.0204</td>
</tr>
<tr>
<td>$Q_{SD}$</td>
<td>13.9173</td>
<td>0.6410</td>
<td>0.0207</td>
</tr>
</tbody>
</table>

6.2.1.1 Do the MWT results concur with wind erosion physics?

In 1941, Bagnold suggested that particle-size could be used to describe the velocities required to initiate particle movement, and that 90 µm particles required the lowest friction velocity to initiate sediment movement. Of the four field sites tested in this experiment, the dune had modal sizes coarser than 90 µm and the three claypan sites were finer than 90 µm. This means that the dune and claypan sites were positioned on either side of Bagnold’s curve for fluid velocity ($U_f$). The particle size at the soil surface of the sand sheet was coarser than the washout and sealed clay, meaning that the dune and sand sheet have similar fluid velocities (Table 6.6). In terms of fluid velocities, both the washout and sealed clay sites were the least-erodible surfaces of the four (Table 6.6). Once saltation material was added, however, the impact velocities ($U_i$) were greatly reduced for the finer claypan surfaces. It would be
expected that the addition of saltation material on the washout and sealed clay would therefore increase the sediment flux. The measured MWT values show this trend.

Table 6.6. $U_f$ and $U_i$ are the derived fluid and impact velocities as described by Bagnold (1941).

<table>
<thead>
<tr>
<th>Particle size mode (µm)</th>
<th>Dune</th>
<th>Sand Sheet</th>
<th>Washout</th>
<th>Sealed Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200</td>
<td>40</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>$U_f$ (cm/m²)</td>
<td>20</td>
<td>20</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>$U_i$ (cm/m²)</td>
<td>15</td>
<td>8</td>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>

6.3 Modelled erodibility

The Wind Erosion Assessment Model (WEAM) is a physically-based numerical model that uses wind tunnel experiments to explore wind erosion theory. The model is fully described in Shao et al., (1996). In brief, the model aims to account for the combined effect of the four main interacting processes that govern wind erosion: climate, soil, vegetation and land use (Shao and Leys, 1998). It is used in this thesis for two reasons:

- As a baseline comparison of the theoretical sediment loss from each soil
- As a measure of the impact of particle-size. Although there are a number of input variables into the model (see below) only the value for particle-size is modified between the sites for this work. Therefore the model is actually displaying the effect of particle-size.

From a physics perspective, wind erosion is the result of two opposing forces:

1. The capacity of the wind to initiate and sustain erosion
2. The ability of the soil to resist erosion.

The physical quantity used to cause and sustain erosion is the friction velocity $u_*$, which represents the wind shear, or drag, on the soil. The ability to resist erosion is measured by the threshold friction velocity $u_{*t}$, which defines the minimum friction velocity required for erosion to occur. Wind-flow conditions and surface roughness determine $u_*$, while surface factors such as soil texture, aggregation and moisture determine $u_{*t}$. These fundamental concepts underpin WEAM. The empirical parameters used within WEAM include:

- a soil parameter consisting of particle-size distribution, soil mobility and soil type
- a climate parameter consisting of rainfall, evaporation and wind speed
• a vegetation parameter consisting of frontal-area index and vegetation height; and
• a land-use parameter.

Each parameter directly influences either the threshold friction velocity or the friction velocity, and they are used to calculate the sand or dust flux (Q).

According to the model, the most important factors influencing \( u_\tau \) are the frontal-area index of surface-roughness elements (\( \lambda \)), soil moisture (\( w \)), soil particle-size (\( d_s \)), and surface crusting (\( S_c \)). Combining these, the \( u_\tau \) routine is parameterised for a given \( d_s \) as:

\[
 u^* (d_s; \lambda, w, c) = \frac{u_\tau^*(d_s;0,0,0)}{R(\lambda)H(w)Sc} \tag{6.3}
\]

\( Sc \) is a measure of surface crusting (estimated and set to ‘no crust’ for agricultural soils), \( R(\lambda) \) is the ratio of \( u_\tau \) with no cover to \( u_\tau \) with cover, and describes the sheltering effect of surface roughness as determined by Raupach et al., (1993). \( H(w) \) is the ratio of \( u_\tau \) when the soil is wet to \( u_\tau \) when the soil is dry (estimated with empirical relationships) and \( c \) is a constant of order 1.

While WEAM was developed to incorporate a number of parameters, it does not describe all parameters that control soil erodibility and cannot, therefore, provide a perfect assessment of erodibility. Rather, it is used here to provide a baseline assessment of the erodibility of the four field sites (dune, sand sheet, washout and sealed clay). In running the model, all parameters except particle-size were kept constant. Sediment fluxes (Q) were based on a wind with \( u_* \) of 0.8 m/s.

Initially, WEAM was applied to the four field sites based on particle-size characteristics of the top 10 mm of soil. This sampling depth characterises the erodibility characteristics of the soil \( (E_{soil}) \). Sandy soil (dune \( E_{soil} \)) has the potential to erode at five times the average rate of loam (claypan \( E_{soil} \)) (Table 6.7). A bare dune of coarse sand is easily remobilised by the wind, while finer claypan sediments require greater wind speeds to move them. The diversity of crusts within claypan surfaces also highlights that the subtle textural differences between them impact the model fluxes. There are smaller, but potentially still significant, differences between the \( E_{soil} \) of the claypan sites. The finer-textured sealed clay is theoretically capable of yielding more sediment than the washout and sand sheet (Table 6.7).
Table 6.7. Sediment fluxes (Q) as calculated with the Wind Erosion Assessment Model for four soil surface forms for the bulked topsoils ($E_{soil}$).

<table>
<thead>
<tr>
<th>WEAM Q (g/m/s) $E_{soil}$ (0 – 10 mm)</th>
<th>Dune</th>
<th>Claypan</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.38</td>
<td>0.07</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Sand Sheet</th>
<th>Washout</th>
<th>Sealed Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03</td>
<td>0.08</td>
<td>0.11</td>
<td></td>
</tr>
</tbody>
</table>

6.3.1 Erodibility characteristics of the soil vs. soil surface

The differences in the modelled sediment flux of the $E_{soil}$ are strongly influenced by soil particle size, as this was the only variable changed when running WEAM for each of the soil surfaces. Traditionally, soil sampling in cultivated fields uses bulked samples amalgamated from a range of depths (commonly 0–10 cm). However, as a rangeland surface does not experience cultivation disturbance it could be argued that samples at the soil surface would have different characteristics to samples collected at depth. Rangeland surfaces commonly forms crusts between 1–8 mm deep, depending on formation processes. Surface crusts have been shown to vary from the underlying sediment structurally (Gillette, 1977; Goossens 2004), texturally (Zobeck, 1991), chemically (Okin et al., 2001), and biologically (Belnap, 2003). Each of the four surfaces tested had a crust of variable thickness and origin. As WEAM is particularly sensitive to texture, it was important to estimate the modelled sediment flux using the soil surface characteristics ($E_{surface}$).

The modelled sediment fluxes for the soil surface characteristics ($E_{surface}$) highlight the sensitivity of the model (Table 6.8). It is possible to distinguish coarse-scale differences between the dune and claypan sites, but potentially not the fine-scale differences expected within the claypan sites. The dune surface has the potential to erode at a rate ten times greater than the average of the claypan sites (Table 6.8). This erodibility rate is twice the difference between the dune $E_{soil}$ and associated claypan $E_{soils}$. This represents a reduction in the mean particle-size characteristics of two of the claypan sites: washout and sealed clay. Although there is a reduction of the modelled sediment flux expected to be emitted, the modelled dune flux halved. At this elementary level of analysis, at least, it would appear that there are major differences based on sampling depth. Particle-size characteristics appear to drive these differences.
Table 6.8. Sediment fluxes (Q) as calculated with the Wind Erosion Assessment Model for four soil surface forms for the soil surface (E_surface).

<table>
<thead>
<tr>
<th>WEAM Q (g/m/s)</th>
<th>Dune</th>
<th>Claypan</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_surface (0 – 2 mm)</td>
<td>0.197</td>
<td>0.02</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sand Sheet</th>
<th>Washout</th>
<th>Sealed Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.04</td>
<td>0.006</td>
<td>0.015</td>
</tr>
</tbody>
</table>

6.4 \( E_{soil} \text{ characteristics: particle-size} \)

The WEAM results indicated that differences in particle size produced differences in the calculated sediment flux, as subtle changes between the sites produced differences in the model outputs. Much could therefore be learned from conducting high-resolution particle sizing. This would help our understanding of erodibility by providing geomorphic interpretation along with clues as to each soil’s provenance.

All particle-size analyses were performed using a Multisizer 3, a precision electronic sizing instrument based on the Coulter Principle (Miller and Lines, 1988). This particle-sizing instrument allows very-high-resolution analysis (up to 256 size classes per sample) with an analytical size range from 0.4–600 µm (McTainsh et al., 1997). Particle-size analyses were conducted on:

- dune bulked topsoil (10 mm deep - \( E_{soil} \)) and soil surface (5 mm deep - \( E_{surface} \))
- sand sheet bulked topsoil (10 mm deep - \( E_{soil} \)) and soil surface (4 mm deep - \( E_{surface} \))
- washout bulked topsoil (10 mm deep - \( E_{soil} \)) and soil surface (2 mm deep - \( E_{surface} \)); and
- sealed clay bulked topsoil (10 mm deep - \( E_{soil} \)) and soil surface (1 mm deep - \( E_{surface} \)).

The bulked topsoils (\( E_{soil} \)) of the study area could be divided into two groups: sandy soils of the dune, and clay loams of the claypan. The particle size of the dune soil had a mode of around 200 µm (Figure 6.4), whereas mode of the claypan soils was 40 to 50 µm. The three claypan sites had only subtle particle-size differences. The sand sheet was slightly finer (primary mode of 28 µm and secondary mode of 6 µm) than the washout (primary mode of 50 µm) and sealed clay (primary mode of 50 µm) (Figure 6.4).
The differences in the particle-size distributions (PSDs) of the bulked topsoils ($E_{\text{soil}}$) were as expected. Dune sands were coarser than clay loams, and the WEAM results confirmed that such differences can cause different emission fluxes.

The WEAM results also indicated that sediment flux was reduced between the bulked topsoil and the soil surface. These changes can be related to particle size, as this was the only parameter that changed between analyses. Knowing something about the particle-size distribution enables interpretation of the geomorphic processes and provenance processes acting upon the soil that produce its surface characteristics. High-resolution analysis is necessary to create such particle-size distributions.

In order to give the interpretation of PSDs greater independent rigour, a statistical package was used. While studying dune sands in the Simpson Desert, Folk (1966) proposed that soils are made up of ‘populations’ of particle sizes, with each population reflecting its source area. Leys et al., (2005) tested a curve fitting programme, MIX 3.1 (Macdonald and Green, 1988), by experimentally mixing sediment populations and attempting to distinguish the populations within the mix. While MIX was good at identifying the large populations, particularly on the distribution edges, it did not perform as well with smaller populations in the middle of the distribution (Leys et al., 2005).
Perhaps one of the greatest strengths of MIX is that the populations can be interpreted as being derived from either a provenance or a process. Analogous to DNA, province is a ‘measure’ of where the sediment has come from. The particle-size characteristics will allude to the formation and source area. If however the sediments are moved through geomorphic processes, these province characteristics can be changed in a systematic manor thus providing a powerful geomorphic interpretation tool.

For example, Livingstone et al., (2006) used MIX to analyse population changes across a dune. The results showed wind fining of sediment distributions across the surface (Livingstone et al., 2006). The four field sites in this study (dune, sand sheet, washout and sealed clay) represent greater geomorphic complexity than a single dune because of the interactions between the fluvial and aeolian systems both spatially and temporally. High-resolution particle sizing, coupled with MIX analysis, was used to help identify the subtle differences in PSD between the bulked topsoil and soil surfaces.

6.4.1 Dune particle-size

The particle-size of the dune is examined in terms of the bulked to soil particle-soil (which strongly influences \( E_{\text{soil}} \)) and the soil surface particle-size (which strongly influences \( E_{\text{surface}} \)).

A coarse particle-size population of around 200 µm dominates the bulked topsoil of the dune, with a finer tail extending to 2 µm. By contrast, the soil surface has a dramatic reduction in the coarse population and an increase in the fine tail. Two populations within the finer tail begin to dominate the particle-size distribution of the soil surface (Figure 6.5).

The MIX analysis showed that the coarse population accounted for 66 percent of the total particle distribution within the bulked topsoil. This in turn was composed of two populations, with modes of 155µm and 208 µm. The fining of the soil surface is clearly seen with the combined proportion of the 155µm and 208 µm modes reduced to 25 percent of the distribution. An increase in the 17–25 µm modes occurred, from 15 percent in the bulked topsoil to 52 percent in the soil surface (Figure 6.5).
Figure 6.5. Particle size distributions of the dune topsoil and soil surface. Both distributions are minimally dispersed with the soil surface representing a surface layer of 2 mm. Modal positions of populations identified with MIX are indicated with triangles.

6.4.1.1 Possible source of fine sediment inclusion on dunes

A fine population is not necessarily common in dune sands, suggesting that it had been deposited from elsewhere. Flood deposits high on the dune crests have not been recorded and seem unlikely. Aeolian deposition is, however, a plausible source of this fine material. A dust flux study conducted by McTainsh et al., (1999) at the LC claypan concluded that weekly changes in suspended dusts were similar on the dune and claypan. They interpreted this as transport of sediment from the claypan to the neighbouring dune, but without information on the particle-size populations, this is simply speculation. In addition, their study used wind-vane sampler sediment traps, which are inefficient at collecting sediment finer than 40 μm (Shao et al., 1994). In order to determine if the finer sediment detected in the MIX analysis
was in fact transported from the claypan, a particle size and MIX analysis was made of sediment collected using deposition traps. Three traps were set up, two on the claypan encompassing a range of dust source areas and a third on the dune approximately 2,500 m from the claypan sites. The traps were set at a height of two metres to minimise the collection of any dune sediments.

The deposition rates on the two claypan sites on the LC claypan (displayed as a range in Table 6.9) and on the neighbouring dune site demonstrate that the majority of dust deposition occurs on the claypan (Table 6.9). On average, deposition rates on the dune were half those of the upper range of claypan deposition, supporting the findings of McTainsh et al., (1999).

<table>
<thead>
<tr>
<th>Date</th>
<th>Claypan</th>
<th>Dune</th>
</tr>
</thead>
<tbody>
<tr>
<td>13/08/96</td>
<td>0.4193–0.0262</td>
<td>0.0119</td>
</tr>
<tr>
<td>27/08/96</td>
<td>0.0028–0.0021</td>
<td>0.0038</td>
</tr>
<tr>
<td>5/09/96</td>
<td>0.0043–0.0063</td>
<td>0.0022</td>
</tr>
<tr>
<td>23/09/96</td>
<td>0.0153–0.0061</td>
<td>0.0114</td>
</tr>
<tr>
<td>7/10/96</td>
<td>0.0215–0.0162</td>
<td>0.0167</td>
</tr>
</tbody>
</table>

The PSDs of deposited dusts on the claypan and dune provide additional, independent support for the hypothesis that claypan dusts were being deposited on the dune. The PSDs of the deposited dusts indicate shared populations between the claypan and dune deposition sites (Figure 6.6), but significantly different properties. The claypan dust had two populations:

- A population at 48 µm, dominating the distribution (67 percent)
- A smaller population (33 percent) at 19 µm

The dune dust had three populations:

- Modes at 42 µm and 19 µm, making up 53 percent of the distribution
- A smaller population at 8 µm

The deposition of fine populations on the dune alters the particle-size characteristics of the soil surface. Such textural changes to the soil surface have the potential to alter the soil surface erodibility to wind.
6.4.2 Sand sheet particle size

The particle-size of the sand sheet is examined in terms of the bulked to soil particle-soil (which strongly influences $E_{\text{soil}}$) and the soil surface particle-size (which strongly influences $E_{\text{surface}}$).

The sand sheet bulked topsoil is dominated by a population with a 40 µm mode and a secondary mode at around six µm. The particle-size distribution of the soil surface shows very little difference from the particle-size distribution of the bulked topsoil (Figure 6.7).
Figure 6.7. Particle-size distributions of the sand sheet topsoil and soil surface. Both distributions are minimally dispersed, with the soil surface representing a surface layer of 2 mm. Modal positions of populations identified with MIX are in microns and indicated with triangles.

Analysis with MIX showed three populations existing in the bulked topsoil at 6, 28 and 36 µm. These three populations also appear in the soil surface with some slight modal variations. The similarity between the PSDs indicates that there is no evidence of an increase in fines similar to that which appeared on the dune surface. This is perhaps inconsistent with the apparent deposition and accumulation of fines on the dune, considering that the sand sheet is on the claypan and would therefore also receive deposited sediment. Even the lowest end of the claypan deposition rate is higher than that recorded on the dune (Figure 6.6). This apparent anomaly could be explained by the much younger age of the sand sheet surface (estimated at 3–5 years) compared with the more stable dune surface (estimated at a minimum of 20 years). In effect, the sand sheet has had less time to accumulate deposited dust.
6.4.3 Washout particle-size

The particle-size of the washout is examined in terms of the bulked to soil particle-soil (which strongly influences $E_{\text{soil}}$) and the soil surface particle-size (which strongly influences $E_{\text{surface}}$).

The washout bulked topsoil is dominated by a population around 50 µm with a finer tail extending beyond 2 µm. The soil surface displays a shift in the entire distribution which becomes finer overall. The coarser end of the bulked topsoil disappears, resulting in a mode of around 20 µm dominating the soil-surface distribution (Figure 6.8).

Analysis with MIX shows that the bulked topsoil is dominated by two populations, 25 and 48 µm, accounting for 84 percent of the distribution. The fining of the soil surface is clearly seen with the disappearance of the 48 and 104 µm populations and a fining of the 25 to 18 µm population. The 18 µm mode dominates the distribution at 78 percent.

![Washout bulked topsoil vs. soil surface particle-size analysis](image)

Figure 6.8. Particle-size distributions of the washout topsoil and soil surface. Both distributions are minimally dispersed with the soil surface representing a surface layer of 2 mm. Modal positions of populations identified with MIX are in microns and indicated with triangles.
This surface fining is unlikely to be due to dust deposition (as inferred for the dune), as the washout surface is considerably younger than both the dune and the sand sheet (<1 year), allowing insufficient time for significant dust deposition. A more likely interpretation is that the particle size of this surface reflects its fluvial origins. As examined earlier, the field evidence indicates that the washout was formed by the fluvial reworking of a previously-large coppice dune/sandy hummock. This fluvial reworking would have involved the selective removal of fines in runoff and their redistribution over the washout surface.

### 6.4.4 Sealed clay particle size

The particle-size of the sealed clay is examined in terms of the bulked to soil particle-soil (which strongly influences $E_{\text{soil}}$) and the soil surface particle-size (which strongly influences $E_{\text{surface}}$).

A population of around 50 µm dominates the sealed clay bulked topsoil with a finer tail extending beyond 2 µm. The soil surface displays a shift in the entire distribution and becomes finer. The coarser end of the bulked topsoil disappears and the distribution becomes very broad with multiple modes appearing (Figure 6.9).

Analysis with MIX shows that the bulked topsoil is dominated by two populations, 28 and 52 µm, accounting for 73 percent of the distribution. Fining of the soil surface is clearly seen with the disappearance of the 52 µm population and the appearance of fine populations at 1, 4 and 7 µm.
Unlike surface fining in the washout sample where the shape of particle-size distribution remains similar but the principal modes become finer, sealed clay produces a broad, flat distribution. This distribution could be geomorphically produced through fluvial reworking of the bulked topsoil. Once hydrated, the fine clay material that forms well structured aggregates at depth are brought into suspension. Once in a particulate state, the clays spread across the soil surface, forming a very thin physical crust. This breakdown of clay aggregates is exacerbated by salinity-induced slaking.

Chemical breakdown of clay aggregates is a common laboratory technique used to determine the 'elemental’ particle-size distribution of a sample. Both sodium and calcium salt solutions...
are added to the soil sample and agitated for a number of hours. The resultant particle-size
distribution of a 'fully dispersed' sample will have the same effect as in

Figure 6.9. Clay aggregates that behave as fine sands dissociate and show particle-size fining.
In the field setting, salts brought to the surface through hydration result in slaking. Particle-
size distribution may reflect current salt levels, with greater fining resulting from increased
salt levels.

6.5 \textit{E}_{\text{surface}} characteristics: crust strength

Surface strength, determined with a penetrometer, is frequently used as a measure of crust
hardness. While the vertical force applied with a penetrometer is viewed as the ability of a
crust to resist saltation impacts, it does not account for shear stresses between soil particles.
Ideally both vertical and horizontal forces should be tested when determining crust strength, but
it is quite often the case where only one is used as an indicator of its relative erodibility. Shear
stress testing has occurred in the laboratory using microprocessor controlled instrumentation
(McKenna Neuman \textit{et al.}, 1999) however the use of a portable shear stress device in the field
would pose challenges with working with thin crusts. Field testing of both vertical and
horizontal forces on crusts is difficult; perhaps even more the reason to attempt to conduct
both measures in the field. Unfortunately this thesis only reports vertical strength as tested in
situ with a GeoTechnic pocket penetrometer using a tip diameter of 6 mm. Three hundred
randomly-allocated measures were made at each of the field sites. Soil moisture was not taken
along side of the penetrometer readings. This should perhaps routinely be done but was not
seen necessary at the time of sampling as rainfall had not fallen for 7 weeks prior sampling.
Units of crust strength are expressed in kg cm$^{-2}$.

The dune crust had the greatest surface strength of the four tested surfaces (Table 6.10). The
strength of the crust reflects both the particle-size characteristics and the biological
components. The particle-size distribution for the dune crust displays inclusion of fine
material, resulting in a broad range of particles. This fine material probably derives from
deposition of dust from the adjacent claypan (as discussed above). Broad particle-size
distributions in soils result in well-packed sediments, and therefore greater strength. The
inclusion of fine sediments also gives cyanobacteria a greater opportunity to persist (Yair,
1990). On a dune, light penetrates deeper into the soil profile, allowing the cyanobacteria to
colonise the sediments to a greater depth (Garcia-Pichel and Pringault, 2001). Surfaces that
remain stable for long time periods maximise crust persistence and produce a more developed crust surface. Field observations and anecdotal evidence indicate that the dune crusts in this study are greater than ten years old, thereby maximising the cyanobacteria community composition and crust strength.

Of the claypan surfaces, sand sheet had the lowest crust strength and sealed clay the highest (Table 6.10). As we have seen, the sand sheet has a uni-modal particle-size distribution, and therefore lacks the strength imparted by fine sediments. This uni-modal distribution highlights the well-sorted nature of the sediments. The low strength of the washout surface reflects the fluvial sorted sediments. In contrast, the sealed clay surface exhibits a broad distribution of particle sizes, and this is reflected in its higher surface strength.

Table 6.10. Mean soil surface strength of four soil surfaces measured with a pocket penetrometer. The standard error is given in parenthesis.

<table>
<thead>
<tr>
<th></th>
<th>Dune</th>
<th>Sand Sheet</th>
<th>Washout</th>
<th>Sealed Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength (kg cm$^{-2}$)</td>
<td>4.6</td>
<td>1.25</td>
<td>1.5</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>(0.09)</td>
<td>(0.04)</td>
<td>(0.04)</td>
<td>(0.05)</td>
</tr>
</tbody>
</table>

Crust strength has been used as a means of characterising resistance to saltation impact (Rice et al., 1997), thereby implying a surrogate measure of erodibility. In this study, however, there was an apparent lack of relationship between measured sediment flux and soil strength. High sediment fluxes were measured from the dune and sand sheet, yet their soil strengths were at opposite ends of the range. While the soil strength measure appears to reflect the particle-size characteristics of the crust, it appears not to respond to crust type. Crusts with higher levels of biological material did not necessarily have increased strength, yet in the field, visual assessments suggested that biological crusted sites tended to be more resistant to particle bombardment.

Other researchers have reported mixed results. Gillette (1978) found soils with well-developed crusts and strong desert pavements were most resistant to wind erosion. McKenna Neuman and Maxwell (2002) demonstrated that penetrometry provided a suitable index of crust strength by providing an approximation of the energy needed to break crusts through saltation. Yet Rice et al., (1997) found that penetrometer tip size was critical when using soil strength as an erodibility surrogate. Using laboratory pin penetrometers, Rice et al., (1997) advocated tip sizes < 1 mm. The laboratory penetrometer relationships were clearly not field robust. Thomas and Dougill (2007) used a field penetrometer to quantify cyanobacterial crust
strength. They found insufficient evidence to relate the measurement of crust strength to erodibility.

In this study, crust strength appeared to bear no relationship to surface type or the surface characteristics associated with each field site. The spatial heterogeneity of the surface characteristics, such as occurrence of fine cracking at each crusted surface, highlights the differences between the sites (Figure 6.10). Non-biological features, either structural crusts or cracks, dominated sealed clay and washout surfaces. The two biological crusted sites were strongly characterised by cyanobacteria cover (Figure 6.10). The presence of structural or biological crusts had little relationship to the crust strength as measured by penetrometer. For example, percentage covers of vesicular crust on the sealed clay and washout were 78 percent and 50 percent respectively, yet the crust strength data indicates that the sealed clay was twice as strong as the washout site. Visual observations of the surfaces after abrasion indicated that most of the erosion occurred along the weaker, thin edges of cracks. Striations, as described by McKenna Neuman et al., (1996) and Rice et al., (1996), were seen at all sites, sometimes randomly across the test surfaces, but usually associated with the fine cracks.

![Figure 6.10. Occurrence of different soil surface features on four soil surfaces tested for their erodibility.](image-url)
6.6 $E_{\text{surface}}$ characteristics: biological crust characterisation

Biological crusts have been shown to reduce wind erosion rates both with field-based wind tunnel studies in the United States, Europe, and Australia (Gillette et al., 1982; Pluis and de Winder, 1989; Williams et al., 1995; Leys and Eldridge, 1998), and laboratory wind tunnel studies in Europe and Canada (Rice et al., 1997; McKenna-Meuman et al., 1996). Control has been linked to:

- the binding of surface grains with either filaments or secretions (Belnap and Gardner, 1993)
- production of biological aggregates (Leys and Eldridge, 1998; Eldridge and Leys, 2003)
- changes in the strength of the crusts (McKenna Neuman and Maxwell, 1999); and
- increases in surface roughness associated with above-ground vegetative biomass (Thomas and Dougill 2007).

Identifying the presence of biological crusts is easy if the organisms are above-ground and conspicuous, but when the community consists entirely of within-sediment species, a number of measures are required to quantify the density of organisms in the soil. To characterise the biological content of the soil both autotrophs and heterotrophs were considered. Autotrophs were characterised solely with chlorophyll $a$ measuring using the methods of Ronen and Galun (1984). Both autotrophs and heterotrophs were characterised with and exo-polysaccharide secretion (EPS) determination using the methods of Lowe (1993) as described in Chapter 3.

Biological crust characterisation revealed that the dune was highly enriched with biological material. The claypan sites displayed a range of crust types, with two groupings, representing both biological and physical crusts. The sand sheet had, on average, three times as much biological material as the washout and sealed clay (Table 6.11). These crusts differed significantly with respect to chlorophyll content ($F_{3,19} = 51.05, P = 0.01$) and crust polysaccharide content (ppm) ($F_{3,19} = 17.33, P = 0.01$). The biological crusts of the dune and sand sheet possessed multiple species of cyanobacteria, contained distinct cyanobacterial layers in the crust surfaces and were often found in association with higher-order plants. The two physical-crusted sites (washout and sealed clay) had low bio-measures and were visually devoid of cyanobacterial layers.
Table 6.11. Mean biological content assessment of four soil surfaces using both exo-polysaccharide content (EPS) and chlorophyll *a* content (Chl *a*). Standard errors are shown in parenthesis. There were significant differences for both parameter at p= 0.05.

<table>
<thead>
<tr>
<th></th>
<th>Dune</th>
<th>Sand Sheet</th>
<th>Washout</th>
<th>Sealed Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EPS (ppm)</strong></td>
<td>27</td>
<td>10</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>(2.99)</td>
<td>(3.32)</td>
<td>(3.03)</td>
<td>(0.77)</td>
</tr>
<tr>
<td><strong>Chl <em>a</em> (mg/cm³)</strong></td>
<td>23.2</td>
<td>18.6</td>
<td>3.6</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>(1.09)</td>
<td>(1.60)</td>
<td>(1.57)</td>
<td>(1.12)</td>
</tr>
</tbody>
</table>

The high sediment flux rates from those surfaces with a biological content (Figure 6.2) are contrary to the expectation from the literature that biological crusts reduce wind erosion rates. This unexpected result suggests that another process, perhaps linked to the biological nature of the crust, may in fact be driving the erodibility of the biological crusts. One such process could be the storage of loose sediment on the soil surface.

### 6.7 *E*<sub>surface</sub> characteristics: loose sediment on the soil surface

Loose sediment on the soil surface has the potential to act as a saltation source, contributing to the breakdown of surfaces during wind erosion events. Each of the four field sites had a different capacity to store loose sediment. The sediment flux measures made with the MWT essentially provided a reading of the loose erodible material (LEM). As the sediment flux runs showed little sign of actual crust breakdown—large flakes collected, striations in the soil surface or pitting around fine cracks—this measurement could also be used as an LEM descriptor. The dune surface had the highest LEM, followed by the sand sheet, with the washout and sealed clay surfaces having very little LEM.

Two different processes may contribute to LEM:

- First, the surface could be associated with an inexhaustible supply of sediment (Shao *et al*., 1993b) as would the case be for a bare dune.
- Second, the aerodynamic characteristics of the surface induce trapping and storage. Roughness elements such as vegetation, micro-topography (Carter, 1976) and the available wind run (Gillette, 1977) all contribute significantly to the ability of an area to either store or supply loose sediment.

Increased roughness has been shown to enhance the trapping of dust (Danin and Ganor, 1997) and saltation sediments (Zobeck and Popham, 1992). Limited work, however, has quantified the relationship between roughness and sediment storage. Using the same study area as this
thesis, McTainsh and colleagues (unpublished) quantified the LEM on various crusted surfaces, correlating it to surface roughness (Figure 6.11). A clear, positive relationship existed, with rougher surfaces storing greater amounts of sediment.

\[ y = 0.119x - 0.0674 \]
\[ R^2 = 0.9927 \]

![Figure 6.11. Roughness heights (mm) versus loose material collect from six different soil surfaces (sealed clay, developing cracking clay, depositional crust, cracking clay with vegetation, gibber, cyanobacteria crust, crusted dune) with vertical suction. (McTainsh unpublished data)](image)

This was confirmed in the current study, as the measured sediment fluxes were highest on those sites with the greatest roughness. Although the dune has a potentially inexhaustible sediment supply, it is the roughness elements provided by both vegetation and crusting which provide the impetus for sediment storage. Similarly, the sand sheet has roughness features, including vegetation and cyanobacteria crusts, producing an ideal sediment storage area. The washout and sealed clay lack the surface features or the sediment supply required to produce a sediment storage area.

Viewing a surface as a roughness element capable of trapping sediment represents a fundamental shift in viewing the role of crusts. Previous wind tunnel studies investigating BSC have compared surfaces with and without intact crusts (Williams et al., 1995; Belnap and Gillette, 1998) or after the surfaces had been disturbed (Leys and Eldridge, 1998). Only the Leys and Eldridge (1998) study introduced saltation material into the tunnel, simulating the effect of saltation impacts. Their results identified that disturbance increased surface roughness and sediment flux. While they did not discuss the influence this had on the source
of saltation material they were able to confirm that their surface roughness was large due to the fracturing of the crusted surface into large pieces.

Field studies measuring sediment flux with traps acknowledge the importance of saltation material. Hupy (2004), working in a similar geomorphic setting to the LC claypan, found that a coppice dunefield was a major source of the sediment which collected in the sediment traps. The combination of increased vegetation cover and soil surface roughness of the coppice dunefield made it a perfect sediment storage area. Hupy found that these storage areas were frequently the sediment source for downwind regions. LEM is also thought to have other important roles other than as an abrader. LEM storage in the form of deposits can create shade to phototrophic organisms growing in the soil. Deposits of sediment can function as a nutrient and seed bed, providing preferential growth sites. These are important attributes of soil crusts, and will be discussed further.

### 6.8 $E_{\text{surface}}$ characteristics: Abrasion resistance

As proposed above, the high sediment fluxes (Q) measured on the biological sites actually reflected the released LEM captured on the soil surface. Whether this meant that the surfaces with high LEM were more susceptible to abrasion required further investigation. Direct comparison between the sites was not possible because they have different substrates, histories and biological components, therefore the data had to be normalised. Abrasion resistance (AR) was used to do this. The abrasion resistance (AR) is expressed as:

$$\text{AR} = \frac{[Q - Q_{\text{si}}]}{Q} \quad [6.4]$$

Using the AR, we can therefore determine whether biological crusts erode at similar rates to physical crusts.

The results of these calculations indicate that the sealed clay and washout crusts are less resistance to abrasion than the dune and sand sheet crusts at a windspeed of 12.5 m/s (or 2000 m/s\(^3\)) (Figure 6.12). Displaying AR across five windspeeds for each crust surface (Figure 6.13) highlights two important aspects of the susceptibility of these crusts to abrasion:

- First, an increase in wind speed only has a small impact on the resistance of the crusts to abrasion.
- Second, the washout and sealed clay crusts had the least resistance to abrasion across all five wind speeds.
Figure 6.12. Abrasion Resistance of four crust forms at windspeed 12.5 m/s.

Figure 6.13. Abrasion Resistance expressed for four crust forms over five wind speeds. Shown is the linear relationship between the wind speed$^3$ m$^3$/s and the abrasion resistance.

An anomaly in this trend, however, was seen on the dune surface. Looking back at response of sediment flux (Q) with increasing wind speed (Figure 6.2), there was an increase in Q as wind speed increased. This is expected as higher wind speeds impart more energy to the surface grains, theoretically resulting in greater flux rates (McKenna Neuman and Maxwell, 2002). Unexpected however is that the abrasion resistance of the dune in Figure 6.13
displayed the opposite trend. As wind speed increased, there was an increased resistance to abrasion.

The resistance to abrasion shown by the biological surfaces has been linked to the strength and elasticity of the crust composition (McKenna Neuman *et al.*, 1996, 2005; McKenna Neuman and Maxwell, 1999; Rice *et al.*, 1996). McKenna Neuman and Maxwell (2002) demonstrated that crust flexibility can influence the force absorbed by saltating particles, with softer, fibrous crusts being able to withstand greater kinetic energy than hard, thin crusts. Although the dune and sealed clay surfaces had similar crust strengths (as measured by compressional strength therefore should consider the implications of measuring shear stress), they had very different fluxes and abrasion resistances. Structurally, the hard crust of the dune is a composite of fines, sands and fibrous organic material (in the form of cyanobacterial filaments). In contrast, the claypan possesses a very thin veneer of clay overlying a hard-packed aggregated sediment. This structural disparity results in the impact of saltation material affecting each surface quite differently, despite their apparently similar strengths. The dune surface offers an element of ‘cushioning’ through the fibrous content and microtopography, while the claypan site experiences greater kinetic energy transferred to the surface with each surface impact, resulting in greater particle impact shock. It would be important to investigate if the shear stress between particles in each crust imparted different strengths.

Underlying these issues are the process of saltation and the mechanism of crust breakdown. Using the information from the laboratory studies of McKenna Neuman *et al* (1996) and Rice *et al* (1997, 1999) (as presented in the introduction of this chapter), the breakdown of either a physical or biological crusted surface could be viewed as the result of three entrainment mechanisms. These are:

1. **Saltation impact entrainment**: The removal of LEM produces a saltation cloud. The kinetic energy delivered to the soil from the saltating particles abrades the surface, removing any partially-exposed grains. Weaker, thin regions are predisposed to damage first.
2. **Flake entrainment**: Large pieces of crust are ruptured and removed as a single, large piece.
3. **Flake undermining of cyanobacteria crusts**: One edge can remain attached, acting as a hinge and flapping in the breeze until fatigue sets in and the piece is separated.
The second and third of these processes are a function of time: the longer the duration of bombardment, the greater the fatigue a crust suffers. Sampling duration, therefore, is an important consideration when interpreting the data. The lack of abrasion on the dune may partly reflect the strength and integrity of the dune crust, but may also reflect the experimental operation of the MWT. Two factors of tunnel operation may have had an impact:

- Tunnel run times were restricted to one minute. This may have been insufficient time to reach a critical abrasion threshold and cause crust rupture on the dune.
- Saltation feed rates rise with increasing wind velocity. Saltation material fed via the saltation silo empties quicker when a faster wind speed is passing below it. While the number of particles remains constant, the rate of delivery changes. The implications of this are not clear.

### 6.9 Erodibility rankings generated from multiple measurements

This study has highlighted the complexity of the erodibility concept. Relying solely on the erodibility output measures would have simply lead to the dune and sand sheet being listed as the most erodible surfaces. These output measures are ‘blunt’ measures which do not allow interpretation of what erodibility characteristics are present and which ones may be driving
the system. Investigation into both the soil erodibility characteristics and the surface erodibility characteristics produced a mixture of rankings. Individually the characteristics are difficult to relate as each represents different processes. In reality, not only are these properties often measured individually, but they are also rarely measured simultaneously. This results in multiple empirical relationships that do not accurately reflect the interdependent nature of erodibility. These measures will now be compared and reviewed in an attempt to present an overall erodibility value for each surface type.

Three methods were trialled to create a multiple-method erodibility ranking:

- a rank order method
- a normalised method; and
- a pooled erodibility model.

Each of these three methods incrementally improves on the others, culminating in the development of a model which takes into consideration interactions between the eight original erodibility measures. The appropriateness of the second and third methods will be tested with a mapping exercise. The erodibility values developed for each test surface will be applied to the 25 km$^2$ LC claypan, producing an erodibility map. These maps will be compared to sediment transport maps of measured sediment from natural wind erosion events.

6.9.1 Rank order method

There was great variation between the eight erodibility measures used in this chapter. Applying a simple numerical ranking scheme, from 1 = lowest erodibility to 4 = highest erodibility (Table 6.12), indicates that the dune and the sand sheet have equal highest ranking. The dune and sealed clay peaked the erodibility rankings three times each, but never for the same measure (i.e. when one had the highest ranking the other was much lower). This is likely a reflection of the vast differences in particle sizes, histories and formation processes between the two. This indicates that different characteristics, or combinations of characteristics, are controlling the erodibility of these surfaces. Despite this, the rank order method is an improvement on using only one measure of erodibility, and, as shown below, is at least able to correctly differentiate the relative variation between measurement techniques. The rank order method found the dune and sand sheet to be the most erodible and the washout the least.
Table 6.12. The rank order erodibility rankings described by comparing output measures and erodibility characteristics across the four field sites. A final tally of rankings is provided.

<table>
<thead>
<tr>
<th>Output Measures</th>
<th>E_{soil}</th>
<th>E_{surface}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment Flux (Q)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saltation Induced Sediment Flux (Q_{SI})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WEAM (0-2 mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface cracking</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bio content (Chl a)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abrasion Resistance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tally</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Dune        | 3 | 4 | 4 | 1 | 2 | 1 | 4 | 2 | 21 |
| Sand sheet  | 4 | 3 | 3 | 4 | 1 | 2 | 3 | 1 | 21 |
| Washout     | 2 | 1 | 1 | 3 | 3 | 3 | 2 | 3 | 18 |
| Sealed clay | 1 | 2 | 2 | 2 | 4 | 4 | 1 | 4 | 20 |

6.9.2 Normalised method

By simply ranking measurement values, the relative differences between values for each measure can be either over or under-represented, as no weighting is applied to each ranking. For example, the measured crust strength on the dune was 3.6 times greater than the sand sheet, yet only 1.3 times greater than the sealed clay (Table 6.10). Therefore, by assigning rankings from 4 through to 1, the relative scale between the values has been lost. An improved approach is to normalise each value with respect to the highest erodibility value for that measurement technique. In other words, the most erodible measurement value is ranked as 1 and the other three values scaled according to the value of their measurement in relation to the most erodible, using a simple ratio of:

\[
\text{Normalised method} = \frac{R_h}{R_x}
\]

where \( R_h \) is the measured erodibility value for the highest ranked surface, and \( R_x \) is the erodibility value for each other surface.

For example, in measuring crust strength (Table 6.10), the sand sheet had the lowest value of crust strength (and therefore highest erodibility measure) at 1.25 kg cm\(^{-2}\). Its normalised value becomes 1. The dune had the lowest erodibility rank with a crust strength of 4.6 kg cm\(^{-2}\). It had a normalised value of 0.27 (1.25/4.6). Working on this assumption, Table 6.13 provides the results of the normalised method.
Table 6.13. The normalised method as described by comparing output measures and erodibility characteristics across the four field sites.

<table>
<thead>
<tr>
<th>Output Measures</th>
<th>E(soil)</th>
<th>E(surface)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment Flux (Q)</td>
<td>WEAM (0-2 mm)</td>
<td>Strength</td>
</tr>
<tr>
<td>Saltation Induced Sediment Flux (QSI)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dune</td>
<td>0.67</td>
<td>1</td>
</tr>
<tr>
<td>Sand sheet</td>
<td>1</td>
<td>0.92</td>
</tr>
<tr>
<td>Washout</td>
<td>0.17</td>
<td>0.62</td>
</tr>
<tr>
<td>Sealed clay</td>
<td>0.07</td>
<td>0.64</td>
</tr>
</tbody>
</table>

If these rankings are tallied for each surface, the normalised value for the dune would be 5.10, the sand sheet 4.51, the washout 3.99 and the sealed clay 3.98. This potentially-improved measure still ranks the dune as the most erodible and the sealed clay as the least.

Erodibility at a landscape scale can be predicted with the values generated from the normalised method. The following discussion provides detailed local field-based evidence from the Lake Constance claypan to demonstrate how this normalised method can be used. By knowing the surface types at the 157 sites spread across the claypan (described in Chapter 5.3.2 as either depositional crust, erosional crust, structural crust, cyanobacteria crust, gibber stone or grassed cracking clay) and knowing how the tested field sites (dune, sand sheet, washout and sealed clay) relate to the surface types allows production of a normalised erodibility map. The relationships between the six surface types and the four field sites are shown in Table 6.14.
Table 6.14. Relationship between the surface types (Chapter 5) and the four field sites (this chapter). Scaling factors were applied to the two surface types which were not specifically tested with the field sites.

<table>
<thead>
<tr>
<th>Surface types</th>
<th>Field sites</th>
<th>Scaling factor</th>
<th>Rationale for scaling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depositional crust</td>
<td>Washout</td>
<td>x 1</td>
<td>N/A</td>
</tr>
<tr>
<td>Erosional crust</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structural crust</td>
<td>Sealed clay</td>
<td>x 1</td>
<td>N/A</td>
</tr>
<tr>
<td>Cyanobacteria crust</td>
<td>Sand Sheet</td>
<td>x 1</td>
<td>N/A</td>
</tr>
<tr>
<td>Gibber stone</td>
<td></td>
<td>(Washout) x 1/gibber cover percent</td>
<td>Depositional crust around gravel</td>
</tr>
<tr>
<td>Grasped cracking clays</td>
<td></td>
<td>(Sealed clay) x 0.2</td>
<td>Use sealed clay as the baseline, cracking clays have a very low erodibility due to blocky soil structure</td>
</tr>
<tr>
<td>Dune</td>
<td></td>
<td></td>
<td>Omitted from claypan applications</td>
</tr>
</tbody>
</table>

Three of the surface types align with three of the field sites. Depositional crusts occurred on the washout field site, structural crusts occurred on the sealed clay field site and cyanobacteria crusts dominated the sand sheet field site (Table 6.14). The three other surface types did not receive the erodibility testing as outlined in this chapter, and therefore do not have representative field sites. Erosional crusts occurred too infrequently across the claypan to warrant testing. Gibber stones, while common across the claypan, proved too difficult to test with the micro wind tunnel due to their surface roughness. The grassed cracking clays are highly aggregated and vegetated, and have effective wind erosion protection. The erodibility of grassed cracking clay is therefore naturally low and did not warrant testing.

As the normalised method is calculated for the field sites (that have had the erodibility measures applied) and the proposed normalised map is based on the surface types, scaling factors needed to be developed for those surfaces types which were not represented by field sites. Surrounding the gibber stones were depositional crusts, therefore the washout factor was substituted for these areas. The stone cover, however, acted as a natural suppressor of wind erosion, which needed to be taken into consideration. The scaling factor used for the gibber stones was the tallied value for the washout normalised method (Table 6.13) multiplied by the inverse of the gibber percent cover. As there was no tested surface similar to the cracking clay, a comparison had to be made to a standard: sealed clay. As grassed cracking clay sites are known to have a low erodibility, an arbitrary scaling factor 0.2 that of a sealed clay was
applied. While it is acknowledged that this scaling factor is arbitrary, the correct value would not be known without thorough erodibility testing.

Following the application of scaling factors to the 157 sites, an erodibility map was generated (Figure 6.15a). On this map, the areas shown to be the most erodible (red) align with the distribution of the cyanobacterial crusts and the least erodible areas (blue) align with the cracking clay regions (Figure 6.15a). Comparison of this pooled erodibility map to sediment transport maps (Figure 6.15b-c) demonstrates similar patterns. The non-erodible cracking clay areas identified in the north-west sector of the sediment transport maps remain low in the pooled erodibility map. Low erodible areas associated with the southern streamline (see Figure 4.3) show up on both the sediment maps and normalised erodibility map. The normalised erodibility map does suggest higher erodibility along the dune flank (bottom left corner) than the sediment maps indicate.

There are sources of errors associated with both the production of the erodibility map and the sediment maps. These sources of errors account for some of the variation between the maps. The normalised map is produced through interpolation using the nearest neighbour algorithm between 157 sites. Just how representative the map is to reality is dependant in part on the spatial distribution of the 157 points. In contrast, however, the sediment maps are interpolated using the same nearest neighbour algorithm from only 40 sediment traps. The sediment maps, therefore, are reporting at an even coarser resolution. These error sources are a post-collection processing issue, and are an ongoing difficulty wind erosion researchers face when trying to relate multidirectional sediment sources to stationary sediment traps (i.e. Where did that sediment come from?).

Despite these sources of error, the normalised method produces an erodibility map which begins to compartmentalise the claypan into erodible regions. This is a major advancement in how the erodibility of a claypan has been traditionally viewed, refining the notion of broad geomorphic regions and highlighting that discrete areas can have higher erodibilities. While the normalised method is an improvement from the rank order method, it still does not consider interactions between the erodibility measures and the effect of vegetation cover.
6.9.3 Pooled erodibility model

An improvement to the normalised measure would be to identify how to weight the different factors and account for interactions between them. Weighting implies that the relative importance of the factor to the process is being taken into account and looking for interactions between the factors acknowledges that the system is extremely complex and dynamic. Although this is an ideal approach to take, at present there simply is insufficient data (and perhaps understanding) to construct such a weighting model. It was proposed at the outset of this project that the use of multiple measurement techniques of erodibility would be advantageous, as erodibility consists of numerous properties interacting through space and time. The rank order method (
Table 6.12) demonstrated that differences do indeed exist between different measures, and the normalised method (Table 6.13) demonstrated that there can be large differences within the measures (i.e. between field sites). Neither the rank order nor normalised method considered the interactions that may exist between the erodibility measurements. In order to address this I develop a model which integrates interactions between the measurement techniques and the effect of vegetation. While this model is in many ways quite immature, it begins to address the complexity of erodibility and hopefully stimulates greater research.

I propose that the rank order method is being driven by two parameters: soil particle-size and LEM. These two parameters dictate the way other parameters interact. Soil particle-size characteristics are essentially inherent to the soil, ie $E_{\text{soil}}$, but as shown in section 6.3, the soil surface can reflect the actions of geomorphic processes. These characteristics will remain reasonably stable for medium to long time periods, from months to years (Note that this assumption works at a generalised time-averaged level of analysis. Greater emphasis on time is given in Chapter 8). The WEAM model (section 6.2) highlighted the significance of particle size, as any difference between the WEAM outputs had to be a direct product of changes in particle size, as this was the only variable in the WEAM model that differed between the four sites. Even the subtle changes between the bulked topsoil and the soil surface altered the modelled sediment flux, highlighting once again the significance of particle size.

The LEM of a site has large implications for its immediate erodibility, and has relationships with other erodibility measures. In both the rank order and the normalised methods, the dune ranked highest. The highest values were received for WEAM, sediment flux, abrasion resistance and LEM (Table 6.12). The high WEAM value can be attributed to the large particle size of the dune sediment. The sediment flux and abrasion resistance can be attributed primarily to the loose material lying on the crusted surface, as first discussed in section 6.4.1. Little break-down of the surface occurred during the MWT runs, implying that the majority of sediment flux consisted of the surface LEM. However, succos (Strong, 1998) used to sample LEM apply a vertical suction, resulting in a higher LEM reading compared to the sediment flux value which is determined with horizontal air flow in the MWT.

Of the remaining measurement techniques on the dune, strength, surface cracking, biological content and abrasion ratio all ranked low (Table 6.12). I propose, however, that the value of each of these measurement techniques will increase if the surface is impacted by saltating
particles. Therefore, a measure of high LEM represents the potential for increased saltation bombardment. As such, there are interactions between the measurement techniques based on LEM as being a driver that could amplify erodibility. For example a ‘worst case’ scenario would be to have a high LEM combined with:

- low soil strength
- high percentage cracking
- low biological content; and/or
- a high abrasion ratio.

A soil surface possessing all of these features would potentially have the highest erodibility.

Taking these drivers into consideration, the normalised method can be extended to create a **pooled erodibility model**. This model makes the following assumptions:

- The results of WEAM are driven by particle size. Soil particle size is essentially an inherent property of the parent soil ($E_{soil}$) and therefore has limited interactions with the other erodibility measures.
- LEM exacerbates the values of strength, cracking, biological content and abrasion ratio and therefore has a multiplying effect.
- Vegetation cover provides an over-riding protective layer against wind erosion. Therefore, after the interactions between the erodibility measurements have been accounted, the percent cover of vegetation needs to be multiplied.

The pooled erodibility model can be expressed as:

$$ P_{Em} = ((P_S + ((C_S + C_r + B_io + A_{Res}) \times LEM)) \times Q_{SI}) \times 1/V_c \quad [6.5] $$

where $P_{Em}$ = pooled erodibility model

$P_S$ = particle-size (as determined by WEAM) ($E_{soil}$)

$C_S$ = crust strength ($E_{surface}$)

$C_r$ = cracking ($E_{surface}$)

$B_io$ = biological content ($E_{surface}$)

$A_{Res}$ = abrasion resistance ($E_{surface}$)

$LEM$ = Loose erodible material ($E_{surface}$)
\[ Q_{SI} = \text{Saltation Induced sediment flux} \]
\[ V_c = \text{vegetation cover (inverse of the percentage cover)} \]

LEM can either be measured with the succo or with the sediment flux run conducted with the MWT. The latter is used in Table 6.15 to calculate the proposed pooled erodibility model.

**Table 6.15. The pooled erodibility model comparing output measures and erodibility characteristics across the four field sites.**

<table>
<thead>
<tr>
<th></th>
<th>WEAM (0-2 mm)</th>
<th>strength + cracking + bio + abrasion ratio</th>
<th>LEM</th>
<th>Abrasion Resistance (QSI)</th>
<th>Tally</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dune</strong></td>
<td>1</td>
<td>1.44</td>
<td>0.67</td>
<td>1</td>
<td>1.96</td>
</tr>
<tr>
<td><strong>Sand sheet</strong></td>
<td>0.2</td>
<td>2.06</td>
<td>1</td>
<td>0.92</td>
<td>2.09</td>
</tr>
<tr>
<td><strong>Washout</strong></td>
<td>0.03</td>
<td>3.12</td>
<td>0.17</td>
<td>0.62</td>
<td>0.35</td>
</tr>
<tr>
<td><strong>Sealed clay</strong></td>
<td>0.08</td>
<td>3.08</td>
<td>0.07</td>
<td>0.64</td>
<td>0.21</td>
</tr>
</tbody>
</table>

The pooled erodibility model value for each field site was calculated by incorporating the appropriate values from Table 6.13 into the equation 6.5. The pooled erodibility model values were assigned to the 157 sites of the Lake Constance claypan conforming to the assumptions made in Table 6.14 to produce an erodibility map. The percent vegetation cover of each site was known and the inverse of this value was used to account for vegetation protection of the surface from wind.

On Figure 6.16a, the areas shown to be the most erodible (red) align with the distribution of the cyanobacterial crusts, and the least-erodible areas (blue) align with the cracking clay regions (Figure 6.16a). Higher-resolution contouring reflects the incorporation of the vegetation cover which acts to reduce wind erosion rates. The pooled erodibility model map indicates increased patchiness in the areas of highest erodibility. This is consistent with field observations. Point sources provide sediment for wide-spread erosion. The sediment maps (Figure 6.16b-c) indicate the areas where sediment has been collected, and do not necessarily indicate erodible areas. Overall, the erodibility model map provides a measure which appears to have field validity.
6.9.4 Upwind LEM contribution to sealed clay

A problem with the pooled erodibility model is that it does not accommodate upwind sediment sources, and instead only predicts erodibility at the measurement site. For example, sealed clay displays all the properties that make it most vulnerable to the impact of LEM (low soil strength, high percentage of cracking, low biological content and high abrasion ratio), yet this surface comes out with the lowest model number, reflecting the low LEM measurement on site. Extension of the pooled erodibility model requires a parameter that could accommodate LEM coming into the system from an up-wind source area. Such a parameter would be difficult to obtain experimentally but can be simulated numerically.
Acknowledging that the pooled erodibility model is characterising the in situ LEM only, Table 6.16 simulates upwind contributions of LEM to a sealed clay site. By increasing the LEM value (sediment flux column) in 5 percent increments, it is seen that the resulting tally increases initially by 48 percent from the starting value. If the amount of LEM coming into the sealed clay site increases to 15 percent of the original value, the pooled erodibility model value increases by 142 percent.

Table 6.16. Four scenarios of increasing LEM coming into a sealed clay site applied with the pooled erodibility model.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>WEAM (0-2 mm)</th>
<th>strength + cracking + bio + abrasion ratio</th>
<th>LEM</th>
<th>Abrasion Resistance (Q_{\text{ab}})</th>
<th>Tally</th>
<th>Percent increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand sheet</td>
<td>0.2</td>
<td>2.06</td>
<td>1</td>
<td>0.92</td>
<td>2.09</td>
<td></td>
</tr>
<tr>
<td>Sealed clay</td>
<td>0.08</td>
<td>3.08</td>
<td>0.07</td>
<td>0.64</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>Sealed clay</td>
<td>0.08</td>
<td>3.08</td>
<td>0.12</td>
<td>0.64</td>
<td>0.31</td>
<td>48</td>
</tr>
<tr>
<td>Sealed clay</td>
<td>0.08</td>
<td>3.08</td>
<td>0.17</td>
<td>0.64</td>
<td>0.41</td>
<td>94</td>
</tr>
<tr>
<td>Sealed clay</td>
<td>0.08</td>
<td>3.08</td>
<td>0.27</td>
<td>0.64</td>
<td>0.51</td>
<td>142</td>
</tr>
</tbody>
</table>

While these percentage increases appear to be large, they need to be interpreted in the context of the very small actual LEM collected from the sealed clay. In reality, the LEM collected on the sealed clay represented only 7 percent of the LEM collected on the sand sheet (Table 6.15). This is a small quantity of sediment. However, a sand sheet losing only 20 percent of its stored LEM could create a large increase in the erodibility ranking of down-wind sealed clay surfaces.

6.10 Summary

This chapter has examined the third objective of this thesis: to determine the erodibility of different soil surface types on a claypan. An important step was to clearly define the components of the erodibility concept.

- Erodibility Concept: Erodibility is the susceptibility of a soil to erosion. There is erodibility inherent to the soil – soil erodibility \(E_{\text{soil}}\) and to the soil surface – surface erodibility \(E_{\text{surface}}\) which interact with each other to produce overall erodibility.
• Erodibility Characteristics: Both the soil and the soil surface have inherent characteristics which contribute to the overall erodibility. Therefore erodibility characteristics should be viewed AND reported as both soil erodibility characteristics \( (E_{\text{soil}}) \) and surface erodibility characteristics \( (E_{\text{surface}}) \).

• Erodibility Output Measures: A number of measurement instruments are used to quantify the amount of sediment lost from a site during erosion, for example, wind tunnels, sediment samplers and even wind erosion event frequencies. The units of their measurement form the erodibility output measures, e.g sediment flux, sediment concentration and dust storm frequency. The erodibility output measures are ‘blunt’ tools (usually a number) which whilst quantifying the overall erodibility do not and can not partition which of the erodibility characteristics are controlling the current erodibility status.

Much information was learnt from the incremental approach taken investigating the different soil and surface characteristics. The major findings of this chapter are summarised below:

• Particle-size differences between the bulked topsoil and soil surface can vary significantly. This suggests geomorphic reworking of the soil surface sediments and provides an understanding of the background controls to soil surface erodibility.

• Common sediment populations exist across the claypan. This means there is commonality of geomorphic processes across the claypan and the sediments are shared amongst the crusts.

• The quantity of loose erodible material (LEM) appears to be an important indicator of surface erodibility. Surfaces with the highest LEM had higher erodibility measures.

• Surfaces which had biological crusts repeatedly had higher erodibility measures. This reflects the complex interaction with the other surface erodibility characteristics and suggests more so that the LEM characteristic is driving these patterns. The presence of cyanobacteria does have a role though, they induce a greater surface roughness maximising storage of fine sediments. It is the release of these sediments that lead to higher erodibility output measures.

• Abrasion resistance support the claim that the thinner, physical crusts had less resistance to abrasion than the biological crusts. This perhaps works in favour of the physical crusts as they had less LEM to act as a natural abrasion source.
• Interaction between the characteristics underlying the erodibility measures exists. Soil particle size underpins the potential erodibility of a surface, while the quantity of LEM exacerbates the effect of surface properties such as strength, number of cracks and quantity of biological material.

This information helps us understand surface breakdown. It also highlights the importance of cyanobacteria crusts in the landscape. These results suggest that the role cyanobacteria play at a landscape erodibility level is perhaps more complicated than previously explored. One aspect of cyanobacteria crusts which has not been discussed with respect to erodibility is that they are living organisms responding to the physical environment around them. The fact that they are living in a harsh physical environment means that they have developed coping strategies. The next chapter investigates how these strategies enable them to survive and whether they could contribute to the erodibility of biological crusts.
Chapter 7. Ecophysiological Responses of Cyanobacteria Crusts

7.1 Introduction

A great diversity of surface types characterises the surface of a claypan. Perhaps the most remarkable and unique of these are the living biological soil crusts (BSCs). BSCs live under extreme growing conditions characterised by large temperature gradients, extended periods of desiccation, high solar radiation, sporadic rainfall and frequent bombardment from saltating particles. To survive such harsh conditions, the BSC organisms have needed to evolve survival mechanisms. Identifying these mechanisms will help our understanding of the environmental factors important for survival, and how deleterious conditions can lead to their breakdown and therefore erosion of crusted surfaces.

Investigations into the ecophysiology of BSCs have concentrated on the conspicuous members of the community—lichens and mosses. Lichens in particular have received extensive research attention over the past three decades, primarily due to the diversity of symbiotic partners that form lichens: either cyanobacteria (cyanobionts) or algae (chlorobionts). Therefore, even though there is very little specific research investigating the ecophysiology of cyanobacterial crusts in an arid soil, knowledge can be gained from the cyanobiont research.

Research into the ecophysiology of BSCs can be divided into five areas:

- production rates
- response to hydration
- response to light
- response to temperature; and
- response to nutrients.

Important research within each of these areas is reviewed here, with general research relating to BSCs presented first followed by specific cyanobacterial crust research where available.
7.1.1 Production rates and photosynthetic activity

Since 1984, understanding of the overall production rates of crusts has been improved using carbon dioxide (CO$_2$) and oxygen (O$_2$) monitoring, while fluorescence monitoring tools have been developed to measure photosynthetic activity (see review in Table 7.1). This growing body of literature is not particular to any given global region. For example, there have been field measurements of CO$_2$ exchange in soil-crust organisms under natural conditions in Israel (Lange et al., 1970), Namibia (Lange et al., 1994b), central Europe (Lange et al., 1997c; Lange 2000a), and the USA (Phillips and Belnap 1998). Production rates of mixed cyanobacteria soil-crust samples have been studied in the USA (Beymer and Klopatek 1991; Jeffries et al., 1993a,b; Garcia-Pichel and Belnap 1996), Venezuelan savannas (San Jose and Bravo 1991), sand dunes in The Netherlands, (De Winder 1990) and Israel (Lange et al., 1993). While some cosmopolitan cyanobacteria species may be common across these studies, generally the broad species-diversity within a crust means that comparison between international studies is difficult due to the lack of specific information about the organisms being monitored.

Reported maximal rates of net photosynthesis (NP$_{\text{max}}$) under optimal conditions vary greatly, and span two orders of magnitude between 0.111 and 11.5 µmol CO$_2$ m$^{-2}$ s$^{-1}$ (Lange 2001). Lichens had the highest rates of photosynthesis, with single species of phycolichens producing between 3.5 and 5.9 µmol CO$_2$ m$^{-2}$ s$^{-1}$ (Lange et al., 1994; 1997a; 1997b). Cyanobacterial assemblages had the lowest NP$_{\text{max}}$ values, ranging from 0.111 (Jeffries et al., 1993a) to 1.5 µmol CO$_2$ m$^{-2}$ s$^{-1}$ (Phillips and Belnap, 1998; Garcia-Pichel and Belnap, 1996; Lange et al., 1992). These values for cyanobacteria are low compared to the average rates of net photosynthesis for C3 crop plants (such as maize, sorghum or wheat), which range from 20 to 40 µmol CO$_2$ m$^{-2}$ s$^{-1}$ (Larcher, 1995). However, in an arid area devoid of higher plants, the carbon production of cyanobacteria represents an important contribution to the arid carbon cycle.

Derived photosynthesis rates have been estimated with pulse-amplitude modulation fluorescence monitoring both in the laboratory and the field. Research has moved from identifying the differences in the moisture compensation levels between photobionts (photosynthetic members of lichen—either algae or cyanobacteria) of lichens (Lange et al., 1989, 1996a; Greene et al., 2002) to identifying the metabolic response to environmental triggers (Leisner et al., 1996; Lange et al., 1996b; Sch lensog and Schroeter, 2001; Pan newitz...
This shift in research has partially been instigated by developments in instrumentation which allow for longer sampling times in the field. In 1996, Leisner et al., used a pulse amplitude modulator (PAM 2000–Walz) to monitor the seasonal fluctuations of lichen activity in the field. By taking background readings continuously and making saturation pulses every 20 minutes (PFD of 3000 µmol m⁻² s⁻¹ and 1 s duration), Leisner et al., successfully monitored the photosynthetic activity of a cyanolichen over a year. Significantly, the study identified that lichen photosynthetic response was reduced by high solar activity (photo system II [PSII] inhibition). Lange et al., (1997) monitored CO₂ respired from a European lichen continuously for a year using a Klapp-cuvette (Walz) and Pannewitz et al., (2003) used a Mini-PAM to monitor the potential activity pattern of snow-covered lichens throughout an Antarctica winter. Also in 2003, Rascher et al., investigated the PSII characteristics of a community of terrestrial cyanobacteria growing on a rock face. Using a Mini-PAM, the researchers were able to distinguish variations in PSII activity across the rock face. They interpreted these results as ecological niches created by a streamline flowing across the rock face, allowing different cyanobacteria species to colonise different parts of the rock face. Bowker et al., (2002) investigated the potential photosynthetic activity of cyanobacterial crusts by measuring dark-adapted $F_v/F_m$, quantum yield of photo system II (PSII). These studies highlight that the physiology of biological soil crusts has been studied using a wide range of methods.

Table 7.1. Studies conducted of BSC material studying their growth and physiology.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Measurement Parameters</th>
<th>Sample &amp; Origin</th>
<th>Instrument</th>
<th>General aim</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lange, Kilian, Ziegler (1986)</td>
<td>CO₂</td>
<td>Europe cyan and algae Lichens Lab Study</td>
<td>BINOS IRGA (Walz assisted)</td>
<td>Vapour vs liquid hydration to reactivate lichens</td>
</tr>
<tr>
<td>Kappen, Schroeter, Sancho (1990)</td>
<td>CO₂</td>
<td>Antarctica crustose lichens Field Study</td>
<td>CO₂ Porometer Walz</td>
<td>Diurnal photo/res changes</td>
</tr>
<tr>
<td>Lange, Kidron, Budel, Meyer, Kilian, Abeliovich (1992)</td>
<td>CO₂</td>
<td>Negev Desert Dune crust (cyano) Lab study</td>
<td>BINOS IRGA (Walz assisted)</td>
<td>Controlled temp, light and water</td>
</tr>
<tr>
<td>Lange, Budel, Meyer, Kilian (1993)</td>
<td>CO₂</td>
<td>Lichens from around the world</td>
<td>BINOS IRGA (Walz assisted)</td>
<td>Vapour vs liquid hydration to reactivate lichens</td>
</tr>
<tr>
<td>Jeffries, Link Klopatek (1993)</td>
<td>CO₂</td>
<td>US rangeland crusts Cyano dominated</td>
<td>Injection into IRGA (ADC)</td>
<td>Response to resaturation</td>
</tr>
<tr>
<td>Authors</td>
<td>Measurement Parameters</td>
<td>Sample &amp; Origin</td>
<td>Instrument</td>
<td>General aim</td>
</tr>
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<td>---------</td>
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</tr>
<tr>
<td>Jeffries, Link Klopat (1993)</td>
<td>CO₂</td>
<td>US rangeland crusts Cyano dominated Lab study</td>
<td>Injection into IRGA (ADC)</td>
<td>Response to dehydration</td>
</tr>
<tr>
<td>Badger, Pfanz, Bude, Heber, Lange. (1993)</td>
<td>CO₂</td>
<td>Europe Lichens Lab Study</td>
<td>LiCor CO₂/H₂O LI6262</td>
<td>Function of the CCM in cyano/ algal lichens</td>
</tr>
<tr>
<td>Lange, Meyer, Zellner, Heber (1994)</td>
<td>CO₂</td>
<td>Namib Desert 3 sp. Lichens Field study</td>
<td>CO₂/H₂O Porometer Walz</td>
<td>Diurnal photo/res changes</td>
</tr>
<tr>
<td>Garcia-Pichel, Belpap (1996)</td>
<td>O₂</td>
<td>US rangeland crusts Cyano dominated Lab study</td>
<td>Microelectrode O₂</td>
<td>Photo/respn of cyano species</td>
</tr>
<tr>
<td>Lange, Belpap, Reichenberger, Meyer (1997)</td>
<td>CO₂</td>
<td>US rangeland crusts 3 Green algal crusts Lab study</td>
<td>CO₂/H₂O Porometer Walz</td>
<td>Controlled temp, light and water</td>
</tr>
<tr>
<td>Phillips, Belpap (1998)</td>
<td>CO₂</td>
<td>US rangeland crusts Cyano dominated Field study</td>
<td>Canopy assimilation chamber PPSystems</td>
<td>Diurnal photo/res changes</td>
</tr>
<tr>
<td>Lange, Belpap, Reichenberger (1998)</td>
<td>CO₂</td>
<td>US rangeland crusts Cyano Lichen Lab study</td>
<td>Minicuvette system Walz (cms400)</td>
<td>Controlled temp, light and water</td>
</tr>
<tr>
<td>Budel (1999)</td>
<td>CO₂</td>
<td>Rock Cyanos 4 continents (3 sites in Australia mentioned)</td>
<td>Minicuvette system Walz (cms400)</td>
<td>Overview of ecology and diversity of rock cyano</td>
</tr>
<tr>
<td>Schreiber, Schliwa, Bilger (1986)</td>
<td>Act Light 20 W/m² Sat. Light 2000 W/m²</td>
<td>Beans Lab study</td>
<td>PAM 101 Walz</td>
<td></td>
</tr>
<tr>
<td>Lange, Bilger, Rimke, Schreiber (1989)</td>
<td>Act Light 150 W/m² Sat. Light 4000 W/m²</td>
<td>Europe Lichens Lab Study</td>
<td>PAM 101 Walz</td>
<td>Comparison of Fluroescence to CO₂</td>
</tr>
<tr>
<td>Luttage, Budel, Ball, Strube, Weber (1995)</td>
<td>Act Light 20 W/m² Sat. Light 2000 W/m²</td>
<td>Cyanorock samples 5 tropical locations Lab Study</td>
<td>PAM 101 Walz</td>
<td>Photosyn depression at high WC</td>
</tr>
<tr>
<td>Leisner, Bilger, Lange (1996)</td>
<td>Act Light 1 W/m² Sat. Light 3000</td>
<td>German Bot Garden Cyanolichen</td>
<td>PAM2000 (Walz)</td>
<td>Seasonal photochemical activity</td>
</tr>
<tr>
<td>Authors</td>
<td>Measurement Parameters</td>
<td>Sample &amp; Origin</td>
<td>Instrument</td>
<td>General aim</td>
</tr>
<tr>
<td>-------------------------------</td>
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<td>-------------------------------</td>
<td>---------------</td>
<td>-------------------------------------------------</td>
</tr>
<tr>
<td>Lange, Leisner, Bilger (1996)</td>
<td>Act Light 1 W/m² Sat. Light 3000 W/m²</td>
<td>German Bot Garden Cyanolichen Field study</td>
<td>PAM2000 (Walz)</td>
<td>Seasonal metabolic activity</td>
</tr>
<tr>
<td>Bowker et al. (2002)</td>
<td>Act Light ? W/m² Sat. Light ? W/m²</td>
<td>Cyanob soil crusts Colorado Field study</td>
<td>PAM2000 (Walz)</td>
<td>Seasonal and spatial variation of cyanobionts</td>
</tr>
<tr>
<td>Rascher, Lakatos, Budel, Lutge (2003)</td>
<td>Act Light 1 W/m² Sat. Light 3000 W/m²</td>
<td>Cyanob rock samples Guyana Highlands Field Study</td>
<td>Mini-PAM (Walz)</td>
<td>Photosynthetic field capacity and ecology</td>
</tr>
</tbody>
</table>

CCM = CO₂-concentrating mechanism; Act Light = Actinic Light (background light); Sat. Light = Saturation Light; Res = respiration; Photo = Photosynthesis

### 7.1.2 Hydration

All long-term field studies revealed that hydration is essential for the biological activity of BSCs to recommence. BSCs respond rapidly to hydration, quickly restoring respiration and photosynthetic capacity. Hydration has been found to differ between functional groups; for example, Chlorophyta and phycolichens are photosynthetically active in water vapour while cyanobacteria and cyanolichens require liquid water to reinstate metabolic activity. Lange et al., (1986) studied 73 different phycobionts and 33 cyanobionts to reach this conclusion. The same phenomenon was found for soil crusts dominated by the cyanobacterium *Microcoleus sociatus* (Lange et al., 1992), and free-living cyanobacteria (Lange et al., 1993), both of which required liquid water to initiate metabolic activity.

Low moisture compensation points (MCPs) are characteristic of BSCs, enabling the organisms to respond to infrequent moisture events. Phycolichens have very low MCPs; for example *Diploschistes muscorum* is able to produce carbon at a water content (WC) as low as 0.04 mm precipitation equivalent (water content on an area basis, 1 m²) (Lange et al., 1997a). Free-living cyanobacteria and cyanolichens require more water to reach their MCPs—the cyanolichen *Collema tenax* has an MCP of 0.22 mm WC (Lange et al., 1998). However, it is difficult to compare the MCPs of cyanobacterial crusts due to the enormous variation in the methods used to express water content. These methods include moisture content, rain
equivalent and percentage thallus content. These various units are given, but are poorly described. For example, a cyanobacteria-dominated crust from the Negev had a high MCP of 0.1 mm (Lange et al., 1992), while Budel, (1999) expresses the thallus content of rock cyanobacteria as equivalent to that associated with ‘x’ mm precipitation.

Saturating crusts with water will hinder photosynthetic activity. Particularly for phycollichens, net production is low when the organisms are fully saturated. CO\textsubscript{2} fixation is hampered under these conditions. This is thought to be caused by increased thallus diffusion resistances due to pathway blockage by water, thus reducing CO\textsubscript{2} supply for the carboxylating photobionts. Experimentation has shown that this CO\textsubscript{2} depression can be overcome by increasing external CO\textsubscript{2} concentrations (Lange et al., 1996), however free-living and lichenized cyanobacteria possess a CO\textsubscript{2}-concentrating mechanism (CCM) that increases the internal CO\textsubscript{2} partial pressure around the carboxylating enzymes. This improves photosynthetic efficiency, particularly at high water contents (similar to C4 plants). In general, the response of soil crust organisms to high water content is highly variable and not well understood (Badger et al., 1993; Lange et al., 1997; Lange et al., 1999).

Net production (NP) and dark respiration (DR) can start within minutes of rewetting a BSC (Garcia-Pichel and Belnap 1996). Fluorescence monitoring also reveals that BSCs are reactivated within seconds of rehydration, attaining final steady state levels from several to 20 minutes post water application (Lange et al., 1989). Three distinct phases of growth are noted when a dry crust system involving a mixture of heterotrophic and autotrophic organisms is rewetted:

1. **A steep burst of CO\textsubscript{2} release**, even in the light. This is thought to reflect a combination of physiological processes including physical and chemical reactions in the soil matrix.

2. **A period in which NP stays relatively constant at a low level**. The duration of this period has been demonstrated to relate to time since the last hydration event (Jefferies et al., 1993a, b).

3. **CO\textsubscript{2} uptake increases, enhancing NP**. Growth of photosynthesising biomass and the improved light exposure on the soil surface has been suggested for the positive production of phase three (Garcia-Pichel and Belnap 1996; Lange et al., 1992).
7.1.3 Light

The optimal light required to maximise NP is highly variable in BSCs. Not only is light essential for growth, BSC organisms frequently appear susceptible to excess light (photoinhibition) (Prasil et al., 1992; Niyogi, 1999; Lange et al., 1999; Harel et al., 2004). Three mechanisms by which cyanobacteria minimise photo damage have been proposed (Cockell and Knowland, 1999):

- **Avoidance:** This strategy is typified by vertical migration of the organism into the soil substratum (Bebout and Garcia-Pichel, 1995; Garcia-Pichel and Pringault, 2001). ‘UV avoiders’ are often the species living at the greatest depths, hiding below the protection offered by the ‘UV protectors’ (Bowker et al., 2002) and the soil matrix itself. A steep vertical gradient of light intensity exists within the uppermost layers of the soil crusts. For example, less than 1 percent of PPFD (measure of light) remains 1 mm below the soil surface (Garcia-Pichel and Belnap 1996). Therefore, considering that many autotrophic organisms live in the soil crust at depths of up to 5 mm (Garcia-Pichel and Belnap 1996), they could be best described as growing in shaded conditions.

- **Repair:** The photosynthetic apparatus is disassembled during desiccation in order to reduce the photodamage which would occur to the apparatus if it remained constructed during periods of high solar radiation and low moisture (Bowker et al., 2002). By dismantling these structures during desiccation, cyanobacteria are able to quickly restore photosynthetic capability without requiring repair upon rehydration. An alternative mechanism is to activate an efficient repair of the photosynthetic apparatus during the hydrated state as and when photodamage occurs, and subsequently induce a state of dormancy while entering the dehydration process (Castenholz and Garcia-Pichel, 2000).

- **Protection:** This strategy involves the synthesis of pigments that either screen incoming ultra violet (UV) radiation (Garcia-Pichel and Castenholz, 1991; 1993) or function to quench free radicals generated by UV radiation (Adams et al., 1993). Three UV radiation protection pigments exist:
  - scytonemins, which are found in the polysaccharide sheaths of terrestrial cyanobacteria;
  - mycosporin-like amino acids (MAAs) located intercellularly in the cytoplasm; and
carotenoids, which are concentrated in the thylakoid membranes, cell walls and cell membranes.

7.1.4 Temperature
There is limited research into the effect of temperature on BSC production. It is generally considered that temperature may have an influence on the rate of carbon production, with the majority of these studies focussing on mosses and lichens. However there are so many different species within the BSC definition that it is difficult to make generalisations. NP is known to exist in soil crusts from the extremes of cold deserts (Antarctica—Pannewitz et al., 2003) to hot deserts (San Jose and Bravo, 1991). NP has been maintained at high rates in thallus temperatures ranging from 2°C (Lange et al., 1992) to 45°C (San Jose and Bravo, 1991). The optimal range is thought to be between 10 and 28°C (Lange et al., 1998). It is difficult to identify any temperature studies directly conducted on cyanobacterial crusts.

7.1.5 Nutrients
Few studies have investigated the growth-limiting effects of soil nutrients on BSCs. In Australia, soils high in calcium carbonate have been shown to support higher proportions of foliose lichens (Eldridge, 1996), while Bowker et al., (2006) have identified positive correlations between lichen moss crusts and the soil nutrients, manganese (Mn), zinc (Zn) and potassium (K) in the Colorado Plateau. Nitrogen-fixing lichens, particularly Collema sp, dominated this site, potentially skewing results, as the high phosphorus (P) demands of N-fixers, coupled with the immobility of the nutrient, make it highly probable that phosphorus would be a limiting nutrient. The authors do comment that the results may be species specific and interactions among community members are important (Bowker et al., 2006). No studies have looked specifically at the response of arid soil cyanobacteria to nutrient inputs.

7.1.6 Summary
In summary, a body of research into various environmental triggers for BSC activity has developed over the past twenty years. Despite this, the research is piecemeal, and provides limited insight into soil cyanobacterial crusts, with no cyanobacteria examples from Australia. This chapter describes a preliminary investigation using new fluorescence monitoring techniques into the response of Australian desert cyanobacterial crusts to water, light and nutrients. Understanding how the cyanobacteria crusts respond to environmental stimuli is essential in order to better appreciate how the organisms influence soil erodibility to wind. It is not in the scope of the thesis to provide an analysis of the ecophysiological
responses at a molecular level; rather, the aim is to identify key climatic triggers that stimulate cyanobacteria at a landscape scale. Discussion will include the perceived importance of environmental factors and how they relate to the local climate. The chapter concludes with a summary of the results and how they pertain to the research questions posed.

7.2 Materials and Methods

Three environmental parameters were examined for their influence on cyanobacterial crusts: hydration, light and nutrients (Figure 7.1). The hydration experiment was preceded by a non-replicated pilot study of the water content at which photosynthetic response ceases. Using this information, a laboratory experiment (Experiment 1) examined the effects of different quantities of water on the photosynthetic response. The influence of light was tested in the field (Experiment 2). Two laboratory experiments were conducted to analyse the effect of nutrients (Experiments 3 and 4).

![Figure 7.1 Suite of experiments analysing the effect of three environmental factors on cyanobacteria crusts](image)

7.2.1 Measurements of potential photosynthetic activity

The development of modulated fluorometry has enabled the automatic and reliable monitoring of photosystem (PSII) fluorescence for long time periods. A suite of fluorometers currently exists, each with specific applications. The Mini-PAM (Walz, Effeltrich, Germany, 1999), originally designed for measurement of vegetation in the field, has been used to monitor lichens (Schlenso and Schroeter, 2001; Pannewitz et al., 2003) and surface rock growing cyanobacterial species (Rascher et al., 2003). The PhytoPam was developed as a 4
wavelength chlorophyll fluorometer which can differentiate between the contributions of green algae, diatoms and cyanobacteria (Walz, Effeltrich, Germany, 2003). The instrument was developed for studies of periphyton and microphytobenthos studies, but has been used in this thesis to investigate terrestrial cyanobacteria crusts. While the PAMs allow detection of potential photosynthetic activity levels, they also provide information about metabolic processes in plants such as light-use efficiency and the possible inhibition of the photo-chemical apparatus. However, questions have been raised about the appropriateness of such metabolic process measures being applied to cyanobacteria (for reviews see Strasser et al., 1995; Campbell et al., 1998; Maxwell and Johnson, 2000). Details of the two pulse amplitude fluorometers used—Mini-PAM and the PhytoPAM—are provided in Chapter 3.

7.2.2 Hydration experiments

The hydration experiments were aimed at identifying the effect of increased water on photosystem II.

Preliminary experiment

The purpose of this experiment was to measure the PSII activity of a cyanobacterial crust over time as it dehydrated. It was expected that as PSII activity would cease once minimum moisture content was reached. A dry 400 mm² piece of claypan crust was placed in a petri dish on top of a four decimal balance in the laboratory. The crust moisture content was determined by a mass balance approach. Water was added to the dry pre-weighed crust until the weight of the water reached the desired percentage of moisture content. The cyanobacteria crusts were collected from LC claypan eight months prior to laboratory experimentation; the crusts had not received any moisture since the last rainfall 4 months before sampling. The crust was hydrated beyond saturation (termed field capacity, the crust profile absorbs as much water as possible with excess water ponding around it) with deionised water which had been triple filtered through 0.2 µm Millipore cellulose acetate filters (referred to from here on as, 3x DI water). Analysis was conducted with external lighting producing background light of 75 µmol m⁻² s⁻¹. The Mini-PAM used saturation light flashes (800 ms, 3000 µmol m⁻² s⁻¹) to determine F, the fluorescence measure of a light-adapted sample, and Fₘ, the maximum light adapted fluorescence after every 15 min saturating light pulse. Sampling occurred over a 5.5 h time period, with fluorescent response recorded automatically by the Mini-PAM and the weight on the balance recorded manually. A change in moisture content was induced by dehydration caused by the lighting, monitored by the change in weight and expressed as the
moisture content percent of the crust. Temperature at the surface of the crust was measured with the Mini-PAM leaf clip throughout the laboratory experiment. The mean temperature was 24.7 °C with a standard error of 0.21 °C (range = 23.0 – 26.6 °C).

**Experiment 1—Hydration in the laboratory**

The results of the preliminary experiment (presented in the results section of this chapter) provided knowledge of the moisture content at which fluorescent response increased and decreased. This information was used to refine and test the question: Is there a potential photosynthetic response of soil cyanobacteria to differing volumes of water? An alternative way of wording this is: Does the amount of water determine how long the organisms remain metabolically active?

To test this, small pieces of crust (~ 200 mm²) were hydrated with three different volumes of water (calculated as per vol/wt ratio) and applied to biologically active and inactive cyanobacterial crusts. Inactive crust samples were heat treated at 101 °C for 2 h, killing the organisms without destroying the structure of the crust samples. The three hydration rates applied were aimed at simulating three rainfall intensities: low rainfall (5 percent water content); high rainfall (60 percent water content); and field capacity (110 percent water content). These were calculated using a mass balance approach to enable accurate quantification of moisture content. Samples were weighed while dry and the weight of water required to bring the samples to predetermined moisture contents was added with a micro pipette. Micro pipettes allowed moisture to be added in increments of 0.01 ml. Measurements were made with light-adapted crust samples held in the leaf clip of the Mini-PAM (Figure 7.2). Samples were analysed in a constant-control cabinet operating at 30 °C and 300 µmol m⁻² s⁻¹. Fluorescence readings were of maximum light-adapted fluorescence, Fₘ', following saturation light flashes (800 ms, 3000 µmol m⁻² s⁻¹).
7.2.3 Light experiments

The light experiments were aimed at identifying whether the photosynthetic activity of cyanobacteria crusts was inhibited by high light conditions.

Preliminary experiment

A series of preliminary day-time fluorescence measures indicated that the crusts across the claypan and dune flank were not responding to hydration. To test whether photoinhibition was limiting the growth, a shading experiment was set up in the field. This involved daily watering and night-time fluorescence monitoring analysis for three consecutive days. Cyanobacteria crusts on the dune flank represent the most developed biological crusts within the LC claypan surrounds, and were therefore chosen as the experimental crusts. Opaque 120 mm diameter plastic (PVC) collars were pushed into the soil surface and 80 percent shadecloth was attached to the top. The crusts were dehydrated prior to testing, and had received no rainfall for two months. Triple-filtered deionised water (3x DI water) was added to the sleeve to field capacity each morning and afternoon, and the shadecloth was replaced and secured. The Mini-PAM was used in conjunction with a specially-designed fibre-optics holder which held the analytical head at an angle of 60° and a constant distance of 8 mm from the soil crust. The position of the holder on the soil surface was pegged out so that the head assessed the same area each night. Potential quantum yield of photosystem II (PSII), \( F_v/F_m \), was measured, where \( F_v \) is maximum variable fluorescence (\( F_v = F_m - F_o \)), \( F_m \) is maximum fluorescence of the dark-adapted crust during a saturation light flash (800 ms, 3000 \( \mu \)mol m\(^{-2} \) s\(^{-1} \)), and \( F_o \) is ground fluorescence of the dark-adapted organisms.
Experiment 2—Pre-dawn light survey in the field

Pre-dawn surveys, as per Rascher et al., (2003), were conducted on the cyanobacterial crusts of the homestead (HS) claypan. The crusts were dehydrated, the last rain (6.4 mm) falling 16 days prior. Samples were hydrated to field capacity (ponding) 60 minutes before dawn using 3x DI water. The Mini-PAM was used in conjunction with a specially designed fibre-optics holder which held the analytical head at an angle of 60° and a constant distance of 8 mm from the soil crust. Potential quantum yield of photosystem II (PSII), $F_v/F_m$, before dawn was measured where $F_v$ is maximum variable fluorescence ($F_v = F_m - F_o$), $F_m$ is maximum fluorescence of the dark-adapted crust during a saturation light flash (800 ms, 3000 µmol m$^{-2}$ s$^{-1}$) and $F_o$ is ground fluorescence of the dark-adapted organisms. The apparent effective quantum yield of PSII ($\Delta F/F_m'$) of light-adapted crusts was calculated as $(F_m' - F)/F_m'$ after dawn, where $F$ is fluorescence of light-adapted samples and $F_m'$ is the maximum light adapted fluorescence when a saturating light pulse, as described above, is superimposed on the prevailing environmental light conditions (Schreiber et al., 1995).

7.2.4 Nutrient experiments

The nutrient experiments were aimed at identifying whether metabolic and PSII activity were influenced by a range of different nutrients. Two randomised plot analyses were conducted in the laboratory. First, the addition of different types of nutrients was tested (Experiment 3), and second, the effect of different sources of water, as a proxy to different nutrients (Experiment 4), was tested.

Experiment 3

Experiment 3 investigated the effect of three different nutrients on the changes of biomass (measured with chlorophyll $a$) and changes in metabolic products of crust growth (measured with polysaccharide and organic carbon concentration). A visual assessment of the surface activity of the cyanobacteria was also made. The greenness index is a simple visual assessment of the intensity of surface greening. Assessment range was from 1 (no surface greening) to 5 (100 percent cover of deep blue-green coloured cyanobacteria). The analytical techniques have been described in Chapter 4. Cyanobacteria crust pieces of 200 mm$^2$ were housed in 30 ml petri dishes, hydrated at 65 percent (weight basis), and the dishes sealed with tape and positioned above a water bath which was kept at 30 °C. Samples received natural
sunlight and were exposed to ambient temperature in a glasshouse. The experiment was conducted over 7 days with five replicates of each treatment. Treatments were:

- nitrogen (25 ppm);
- potassium and phosphorus (7.5 ppm);
- magnesium (17.5 ppm);
- a complete range of micro and macro-nutrients (Bold Basal Growth Medium, Nichols and Bold, 1965) including the above three plus iron, boron, EDTA and other micro-nutrients;
- 3x DI water; and
- control, no hydration.

**Experiment 4**

Experiment 4 was designed to test two responses:

- the impact of water sources with different nutrient contents on the claypan crusts; and
- the impact of time on the metabolic activity of cyanobacteria.

To test whether cyanobacteria soil crusts respond to nutrient-enriched rainfall, 24 x 100 mm² dehydrated soil crusts were grown in gas-chromatography well plates positioned over a water bath in the glasshouse. Four water treatments were randomly allocated to the 24 crusts, creating six replicates of the four treatments. The treatments included:

- no rainfall
- rainfall collected from the brisbane metropolitan area
- Bold Basal Medium (Nichols and Bold, 1965); and
- 3x DI water

To test the impact of time on the metabolic activity of cyanobacteria, five gas-chromatography well plates (as described above) were used and positioned on the water bath in the glasshouse. Sampling occurred on days 3, 7, 15, 22 and 35. Growth was quantified by analysing changes in chlorophyll $a$ and polysaccharide concentration, fluorescence yield, and surface greening (visually assessed). The analytical techniques for chlorophyll $a$ and polysaccharide concentration were described in Chapter 4. Fluorescence yield ($F$) was determined with the Phyto-PAM, which continuously and simultaneously monitored four different excitation wavelengths: $F_{470}$, $F_{525}$, $F_{640}$ and $F_{665}$. Actinic illumination was applied,
amounting to 120 µmol quanta m\(^2\) s\(^{-1}\) of 660 nm light. The potential quantum yield of photosystem II (PSII), F\(_{v}/F_{m}\), was measured with the application of a saturation pulse. Saturation pulses were applied with the actinic light LEDs (660 nm) at an intensity of ~1800 µmol quanta m\(^2\) s\(^{-1}\) of 660 nm. The greenness index was used to provide a quick and immediate response to hydration.

### 7.3 Results and discussion

#### 7.3.1 Hydration of cyanobacterial crusts

**Preliminary experiment**

Maximum fluorescence occurred with hydration between 40 and 80 percent water capacities (Figure 7.3). There was a rapid decrease in both F and F\(_{m}'\) once water content decreased to 14 percent. The response rate to dehydration was matched to the response rate of hydration (Figure 7.3).

![Figure 7.3 Fluorescence parameters (F and Fm') during the hydration and dehydration of a cyanobacterial crust.](image)

**Experiment 1—Hydration in the laboratory**

The purpose of these hydration experiments was to identify whether small hydration events resulted in smaller activity times. To this end, the preliminary experiment was essential in
identifying the moisture content at which the photosynthetic apparatus of the crusts commenced shut-down. The rapid reduction in PSII activity at around 14 percent moisture content (Figure 7.3) indicated demise in the potential photosynthetic capacity. The low moisture content of 5 percent was selected for Experiment 1 after it was hypothesised that it would be an insufficient quantity of moisture to sustain growth. The results showed a clear difference in the duration of PSII activity between the water treatments.

The heat-treated samples did not respond to hydration (Figure 7.4). Instead, $F_{m}'$ oscillated between 15 and 20 units. Low and high-rainfall treatments responded immediately to hydration. The high-rainfall treatment had approximately twice the magnitude of fluorescence excitation as the low treatment, and sustained activity for twice as long: the low-rainfall treatment managed to maintain activity for only about 15 min while the high-rainfall treatment managed up to 50 min. In comparison, the field capacity sample took time to activate and appeared to lag during the saturated state. However, once sufficient moisture was lost, the fluorescence response continued to increase beyond the readings of the other treatments. The field capacity reading continued to rise until monitoring ceased at 70 min.

![Figure 7.4 Fm’ parameters for three hydration treatments (classified as low, high and field capacity[FC]) of inactive (dead) and active (live) cyanobacterial crusts.](image)
The findings support those of other studies in showing that hydration of cyanobacteria is essential for metabolic activity. Once hydrated, the organisms respond rapidly (Garcia-Pichel and Belnap, 1996; Veste et al., 2001; Satoh et al., 2002). Few studies, however, discuss the quantity of water required to initiate growth. Satoh et al., (2002) found that a common desert crust species, *Nostoc commune*, was able to absorb 20 times the initial dry weight in the presence of sufficient water, but only twice the initial sample weight was needed to recover and maintain the activity of PSII. Rock cyanobacteria receiving a moderate rainfall event were noted to shut down their photosynthetic apparatus up to 40 min earlier than after a heavy rainfall event (Rascher et al., 2003).

Variation between the replicates is accredited to variability in surface chlorophyll. Contributing to the surface variability of chlorophyll is the fact that the large soil cyanobacteria, such as *Microcoleous vaginatus*, are capable of regulating their position within the soil profile in order to maximise moisture events (Garcia-Pichel and Pringault, 2001). Cyanobacteria are frequently seen on the soil surface of LC claypan after rainfall events (Figure 7.5). The ability to migrate could result in different chlorophyll cells being analysed with the Mini-PAM as the cyanobacteria move.

*Figure 7.5* The large mobile cyanobacteria moved to the soil surface following rainfall, while overcast conditions still prevail at LC claypan, DNP.

Daily variations in photosynthetic activity of cyanolichens in the Namib desert have been reported by Lange et al., (1994). The cyanolichens always responded rapidly to hydration, but their photosynthetic activity differed from day-to-day according to temperature, solar
radiation and level of hydration. Depending on when the moisture was received, it was possible for the lichens to use more carbon through pre-dawn respiration than was produced during day-time photosynthesis.

The large differences in reported rates of activation of photosynthesis after rehydration have been accredited to a number of factors. Harel et al., (2004) suggested that not all photosynthetic centres reactivated at the same time. He proposed that up to 50 percent of the PSII centres of a desert crust were activated within three minutes of hydration. The activation of the remaining centres happened gradually over 50 minutes. The different types of photosynthetic apparatus proposed by Satoh et al., (2002) respond at different rates after hydration. Phycobiliproteins and PSI complexes recovered within one minute, while PSII activity recovered in two phases (20 min and two hours), after a time lag of about five minutes. An early study by Potts (1994) suggested that the duration of desiccation was an important factor: the shorter the dry phase, the faster the activation of photosynthetic capability. Regardless of metabolic reasons as to why these differences may occur, the physical effect is that cyanobacteria respond differently to different amounts of rainfall.

7.3.2 Effect of light

Preliminary experiment

Lack of PSII response during day-time sampling prompted the preliminary experiment. Despite hydration, fluorescence monitoring in full sunlight failed to monitor photosystem II activity, suggesting perhaps a photoinhibition of the cyanobacteria crust.

Fluorescence monitoring with the Mini-PAM indicated that shaded crusts on the dune flank produced an increasing yield response over three consecutive nights of sampling (Figure 7.6). The shading allowed the cyanobacteria to migrate closer to the surface, with some filaments observed at the surface.
The results of the preliminary experiment confirmed that the crust was capable of being active under less intense light conditions. Extending this finding to processes which occur naturally in the field suggests that precipitation and full sunlight would seldom occur concurrently, as rainfall is associated with cloud cover and reduced solar radiation. Under overcast conditions, the large mobile soil cyanobacteria which do not have UV pigments as protection actively migrate to the surface, turning it green. Laboratory studies suggest that the recovery from photoinhibition and activation of PSII units is achieved only at low light intensities where the rate of PSII repair matches that of photodamage (Prasil et al., 1992; Adir et al., 2003).

**Experiment 2—Pre-dawn light survey in the field**

Hydrating the crusts before dawn when it was still dark did not activate a PSII response. Ten minutes after sunrise, when the light reached 110 PPFD (µmol m\(^{-2}\) s\(^{-1}\)), fluorescence yield increased rapidly. A plateau was briefly reached before yield fell as solar radiation increased (Figure 7.7). Maximum yield occurred when the light intensity was less than 350 PPFD (µmol m\(^{-2}\) s\(^{-1}\))—an hour after dawn—but this was highly variable.
These results are similar to those of Rascher et al., (2003) who investigated cyanobacteria colonising the surfaces of rocks. Conducting a pre-dawn hydration experiment, the rock cyanobacteria were observed to produce similar fluorescence responses: there was no response in the dark after hydration; at dawn PSII activity rose rapidly; as solar radiation increased, PSII activity decreased. The similarities between the two studies suggest that soil cyanobacteria and rock-dwelling cyanobacteria face similar dehydration, UV and temperature pressures. However, strategies used by rock cyanobacteria to protect themselves from UV depend heavily on pigmentation. Migration strategies are confined to spatial distribution across the surface, seeking shelter in shadier micro-aspects. In comparison, the large dominant cyanobacteria present at Diamantina were UV avoiders: they lack UV pigments, instead
opting for migration. The UV migrators in a soil environment use soil depth as a physical refuge. Despite these fundamental differences, Mini-PAM monitoring captured signals of soil cyanobacteria as they moved through the profile. They have been noted to migrate both laterally and vertically in search of both moisture and optimum light conditions (Garcia-Pichel and Pringault, 2001; Garcia-Pichel and Belnap, 1996), which may explain the disjointed fluorescence signal.

### 7.3.3 Effect of nutrients

**Experiment 3**

In Experiment 3, the effects of different nutrients on the metabolic products of crust growth were investigated. Each of the measurement techniques responded differently to different nutrient sources. Cyanobacteria in the magnesium treatment had a higher greenness index, suggesting that the larger mobile species glided to the surface more than with other treatments (Figure 7.8). However, there was no significant difference between the treatments ($F_{4,24} = 0.876, P = 0.30$). The controls did not have any greening on the surface.

Crusts with phosphorus and potassium addition had the highest chlorophyll $a$ (average 15 mg L$^{-1}$), outgrowing the other crusts (which averaged 10 mg L$^{-1}$) by at least 30 percent (Figure 7.8). However, at a 0.05 confidence level there was no statistical difference between the treatments ($F_{4,24} = 1.07, P = 0.19$).

Three treatments had the highest polysaccharide concentration: the complete nutrient mix, the enriched magnesium treatment, and the combination of phosphorus and potassium (Figure 7.8). Nitrogen enrichment alone did not produce any growth different from the addition of DI water. The control (which did not receive water) was significantly different from the treatments. Despite the differences in the means, statistical there was no difference between the treatments at a 0.05 confidence level ($F_{4,24} = 0.934, P = 0.46$).

Loss on ignition (LOI) analysis was used as a surrogate for carbon content (Figure 7.8). There were no significant differences between all samples, including the control, when tested with an ANOVA.
Figure 7.8 The effect of adding various nutrients to cyanobacteria crusts. Various measures used; dimensionless Greenness Index scaled from 1 = no greening to 5 = maximum greening; Chlorophyll a concentration measured in mg/L; Polysaccharide concentration measured in ppm; Organic carbon as measured by loss on ignition expressed as percent weight loss. Displayed are the mean values and their respective SE. No significant differences for all treatments.

There has been limited research into the effects of different nutrients on the growth of BSCs in the field. Phosphorus has been reported to be negatively correlated with a biological soil crust community dominated by lichen moss in southern Utah (Bowker et al., 2006). This was a surprising response considering that phosphorus is an essential nutrient for growth. In the same US study potassium was found to enhance the growth of the crusts, which led the authors to suggest that potassium could be used to assist the growth of biological crusts which have been artificially positioned for land reclamation.

Using chlorophyll concentration as a sole measure of biomass could be misleading, as the concentration of chlorophyll based on area could vary greatly depending on the species composition, species density and state of hydration. In general, however, crusts dominated by cyanobacteria or Chlorophyta have maximum chlorophyll concentrations below 100 mg m$^{-2}$. In soil crusts similar to the current study, Belnap et al., (1994) found maximal rates at 53 mg m$^{-2}$ while Kidron et al., (2000) found chlorophyll a concentrations in Negev sand dunes of 51 mg m$^{-2}$. Garcia-Pichel and Belnap (1996) found that mixed crusts from southern Utah contained 31 mg m$^{-2}$ of chlorophyll a, of which approximately 75 percent of the pigment was
found in the top 2 mm of the soil surface. It is also proposed that there is seasonality to chlorophyll concentration, depending on the species composition (Bowker et al., 2002). Lichens and mosses have higher chlorophyll concentrations, greater than 900 mg m$^{-2}$. This is more than the 500-700 mg m$^{-2}$ values recorded for C3 leaves (Larcher, 1995). Although chlorophyll $a$ concentrations are used as surrogates for cyanobacterial biomass, environmental conditions such as low light (Vincent, 2000) and high light (Oliver and Ganf, 2000) can modify the concentration of chlorophyll $a$ per cell by increasing the cell size. If this adaptation is common across cyanobacteria, the use of chlorophyll $a$ as a measure of biomass may be fraught with difficulties.

**Experiment 4**

The impact of different water sources and time on the metabolic activity of cyanobacteria crusts was examined. Fluorescence yields slightly increased up until day 15 for all three treatments receiving hydration. The yields were similar between the hydrated treatments, suggesting actively photosynthesising cells (Figure 7.9). Values generally peaked after 15 days’ growing time, after which all treatments declined. The control registered very little signal in the first two weeks and no signal in the last.

![Figure 7.9. The effect of different water types on fluorescence yields. The water treatments, BBM = Bold Basal Medium; DI = Deionised water; NO = no water control; RF = Natural rainfall collected in Brisbane. Displayed are the mean values and their respective SE for the unitless fluorescence yield parameter.](image-url)
The greenness index of samples increased across the five sampling time periods, suggesting that cyanobacteria migrate to the soil surface, peaking after 8 days’ growth (Figure 7.10). All the hydrated treatments displayed a similar trend, with a peak in greenness at day 8 and then a decline over the next three weeks of sampling. The cyanobacteria were observed to remain at, or near, the surface on many of the samples, but faded from the vibrant green colour associated with the day 8 peaks. To why the cyanobacteria faded in colour is unknown, particularly considering that there was still moisture in the crust. Slight variations in moisture content have found to alter the physiological state, as shown in Figure 7.3. Bio-chemical changes could be occurring to the outer cyanobacteria sheaths after day eight causing a fading in colour. Whatever the primary cause for such fading, it was unexpected and not investigated in this work. There is no doubt however that slight variations in moisture content could contribute to the variable results. The cyanobacteria of the control surface did not display any sign of migration and hence no greening of the surface.

![Figure 7.10 The effect of different water types on greenness index. The water treatments, BBM = Bold Basal Medium; DI = Deionised water; NO = no water control; RF = Natural rainfall collected in Brisbane. Displayed are the mean values and their respective SE for the dimensionless Greenness Index scaled from 1 = no greening to 5 = maximum greening.](image)

Chlorophyll $a$ through time is higher in crusts that received Bold Basal Medium (BBM) (Figure 7.11). This treatment consistently out-performed the other water sources with respect to chlorophyll $a$ concentration, but not significantly. Both the values and temporal patterns
were similar for the deionised and rainfall treatments. The control displayed similar patterns but had lower values compared to the DI and rainfall treatments.

**Figure 7.11** The effect of different water types on chlorophyll a concentration. The water treatments, BBM = Bold Basal Medium; DI = Deionised water; NO = no water control; RF = Natural rainfall collected in Brisbane. Displayed are the mean values and their respective SE for the chlorophyll a concentration measured in mg/L.

The treatment with no rainfall had the highest polysaccharide concentration after the first 3 days (Figure 7.12). The concentration of polysaccharides was noted to decline through time in the other treatments also. The Bold Basal Medium treatment deviated from this trend by increasing during the last three weeks of sampling.
Each of the water treatments initiated a change in the measured response, with variation both between treatments and within the treatments through time. It can be inferred from this that the nutrients delivered in each of these treatments was sufficient to stimulate a change, but how do the experimental nutrient sources delivered as water treatments here compare to the range of nutrient sources in the field? In an arid environment such as Lake Constance claypan there are three potential sources of nutrients:

1. **Aeolian derived clays and fine organic matter**: This material is high in nutrients and cation exchange capacity.

2. **Fluvial deposits** during the infrequent flood events

3. **Rainfall events**: Nutrients generated either through electrical activity or cleansing of dust from the atmosphere (McTainsh, 1982).

As the background dust levels at Diamantina are high (Nickling *et al.*, 1999), rainfall has the potential to wash dust and nutrients out of the lower atmosphere, contributing significantly to nutrient availability on the LC claypan. Deposition of nutrients from dust into a riverine environment has been shown to occur (Leys and McTainsh, 1999). Australian dust typically is
enriched in elements such as nitrogen, phosphorus and organic matter (Miles, 1993; Leys and McTainsh, 1994; Boon et al., 1998; Leys and McTainsh, 1999). In addition to there being a source of nutrients (dust) and a mechanism which effectively delivers it to the soil surface (rainfall), it has been suggested that biological crusts enhance nutrient enrichment by trapping dust. Dust trapping can be enhanced by both an increase in surface roughness and the secretion of polysaccharides which act as a glue (Danin and Ganor, 1997; Reynolds, 2001). Its deposition, whether in rainfall or trapped dust, could significantly contribute to the nutrient source needed for growth by cyanobacteria in the soil.

Temporal patterns between the measurement techniques highlight three key aspects:

1. Measured chlorophyll concentrations were similar in both nutrient experiments (Figure 7.8 and Figure 7.11) after one week’s growth. This agreement between two independent experiments confirms that the cyanobacteria were actively growing for the duration of the experiment.

2. The general decreasing trend through time of polysaccharide concentration may reflect the impact of the airborne heterotrophic bacteria in the laboratory environment. Many saprophytic bacteria consume polysaccharide secretions. The bacteria could be sourced from in situ populations or contamination. The natural soil fauna are stimulated by phototrophic growth flushes and soil disturbances (Cropper et al., 1985; Buchmann, 2000). Precautions were taken to minimise the effect of non-endemic pathogens impacting the samples by sterilising all equipment and water treatments and retaining the lids on the incubation chambers.

3. The four measurement techniques are measuring two different physiological processes. The chlorophyll \(a\) and polysaccharide measures represent the cumulative growth histories of the cyanobacteria. In comparison, fluorescence yield and greenness index are instantaneous, providing a measure of what is happening now. The non-hydrated control demonstrates this point very well. While both the chlorophyll and polysaccharide measures produced readings, the fluorescence and visual greenness assessment identified that the organisms were not active. Using chlorophyll and polysaccharide alone may have lead to the assumption that dry crusts were actively producing chlorophyll. However, viewing the same time periods with the instantaneous measures indicated no growth.
7.3.4 Physiological growth time scales

The difference between cumulative and instantaneous measures raises the question of whether the physiological processes being analysed occur at that same time scale. If they did occur at the same time scale, similarities in the responses between the chlorophyll, polysaccharide and loss on ignition measures should exist. Differences exist, however, implying that the rates are different. Different physiological processes will activate in response to rehydration in a certain order: vegetative response/respiration, reinstatement of chlorophyll apparatus, secretions of polysaccharide, and diversity of growth forms (Figure 7.13).

Literature exists which supports the notion that different physiological processes will activate sequentially. Vegetative/respiration response has been shown to occur within minutes of hydration, and has been measured with a variety of techniques: CO$_2$ (Budel, 1999), O$_2$ (Schreiber et al., 2002), and fluorescence (Luttge et al., 1995). The vegetative response can be visually confirmed, as the cyanobacteria without UV protection migrate to the surface. Unfortunately, the other processes are not visible and require temporal sampling post hydration. Scherer et al., (1984) suggested that the sequence of recovery was respiration, photosynthesis and then nitrogen fixation. Although Figure 7.13 may reflect a hypothetical response of three different parameters, the shape or time frames of the curves may not be accurate, highlighting instead the potential differences between them. As an example of this concept, the UV screening pigments in terrestrial cyanobacteria have been found to take two to three days to reach optimal levels (Garcia-Pichel and Castenholz, 1993). This can only occur after exposure to UV thresholds and can only take place when the organisms are hydrated and active. In the desert environment this may be infrequent.
Poikylohydric organisms have to use stored carbon resources, via respiration upon hydration, before any carbon can be produced via photosynthesis (Tuba et al., 1996). As such, if the hydration events are too short to allow carbon production, the organisms could be respiring more than they produce. Or alternatively, if the hydration events occur at night time but dry up prior to dawn, all the carbon consumed during night time respiration could result in a carbon deficit for the organism now unable to photosynthesis due to lack of water (Lange, 2001). Adding to this Bowker et al., (2002) observed seasonal differences in the abundance of desert crusts between summer and autumn. Two suggestions were proposed for this seasonality;

- High summer UV rates impede the production of chlorophyll $a$, with energy instead spent on producing UV protection pigments. There have also been examples of UV-B suppressing carbon assimilation without a corresponding suppression of fluorescence measures (Allen et al., 1998).
- Rainfall quantities and rainfall timing reflect seasonal patterns in the study area of Bowker et al., (2002). Summer rain frequently occurring at night time, morning solar radiation rapidly drying the soil surface reducing carbon gains.

If such a respiration to production ratio is reliant on the hydration event, it would seem critical to understand the impact of differing climatic variations, such as the duration of rainfall events, on the organism’s ability to respond in light of the forecasted long-term climate change.
7.3.5 Interpretation of findings and predicted response to local rainfall

Different rainfall quantities (rainfall size events) have been shown to activate different biological components of the desert respiratory network. Following small rainfall pulse sizes, biological crusts contributed up to 80 percent soil CO$_2$ fluxes to the atmosphere. However, following large rainfall events, roots and soil microbes contributed nearly 100 percent of the soil CO$_2$ flux (Cable and Huxman, 2004). In the context of this study, the work of Cable and Huxman (2004) raises some interesting questions. Considering that the photosynthetic response of cyanobacterial crusts differs according to rainfall, and that excessive light limits the time available for photosynthetic activity, is there a difference in photosynthetic time available to cyanobacteria between small and large rainfall events? By placing this question in the context of the dominant form of rainfall occurring in this arid environment, it is seen that there are important implications for the stabilisation of desert soils against wind erosion.

This study has shown that soil cyanobacteria are very responsive to climatic events. Rainfall triggers a near instant response, initiating rehydration of the filaments and movement to the surface, leading to a series of metabolic processes (photosynthesis, polysaccharide secretion, and perhaps nitrogen fixation and pigment secretion). Although these metabolic processes are triggered by rainfall, PSII is activated by light. Maximum PSII activity was found to occur in light conditions between 110 to 350 PPFD (µmol m$^{-2}$ s$^{-1}$). High solar radiation impeded PSII whilst a shading experiment improved PSII activity. Similar results were found with research on rock-inhabiting cyanobacteria in which low light compensation points (< 100 µmol m$^{-2}$ s$^{-1}$) were common and light intensities of greater than 1000 µmol m$^{-2}$ s$^{-1}$ were seen to reduce PSII activity (Budel, 1999; Rascher et al., 2003). These field experiments did not and were not in a position to distinguish between the effects of solar radiation and temperature as the limiting factors to PSII activity.

While the moisture compensation point is important in identifying the rainfall quantities required to activate the cyanobacterial crust, it is the duration of photosynthetic activity which presumably contributes to the longevity of the organism in the environment. Cyanobacterial crusts which are able to survive have a greater potential to contribute to the soil organic matter and stability through the production of biomass and polysaccharide. These factors contribute to soil surfaces being more resistant to wind erosion. This chapter has shown that crusts receiving small quantities of water (5 percent wt/vol) had PSII activity for time periods of less than 15 minutes. Considering the time delay in activating secondary metabolic
processes, these organisms would have only had time to rehydrate and gear up for production before desiccation set back in. Samples receiving greater quantities of water responded photosynthetically in proportion to the quantity of water received. There is an absence of this research in the literature, presumably because it is the moisture compensation point which is seen as the pivotal value with respect to species survival. However, if a landscape-stability approach is taken, the duration of growth becomes important to understand.

A study by Lange et al., (1997) provides pivotal information about the ecological significance of the timing of both hydration and solar radiation. They monitored diel CO$_2$ exchange in European lichens for a number of hydration events. Response to early-morning dew fall resulted in a lichen thallus being well hydrated at sunrise. Net photosynthesis rapidly increased as solar radiation increased, peaking at a PPFD of 253 µmol m$^{-2}$ s$^{-1}$. The lichen was only active for 90 minutes before the solar radiation dehydrated the thallus. A predawn rainstorm, thoroughly wetting the lichen thallus, initiated a 12 hour growing period, during the first 10 hours of which the thallus was supersaturated, suppressing photosynthesis. Maximal activity occurred two hours before dusk. In a third scenario, lichen is moistened by regular, gentle and brief rain showers interspersed by periods of bright sunshine. Net production continuously changed from high rates during times of favourable water content to depressed values due to drying or saturation.

In an arid environment, the size of rainfall events (or pulse) will greatly impact the potential growing time of the cyanobacterial soil crusts. The majority of rainfall events at Diamantina National Park and the nearby town of Boulia are dominated by small pulse events (< 2 mm) (Figure 7.14). Greater than 50 percent of pulse events deposit less than 4 mm of rainfall. These small events must result in a physiological response, leave the cyanobacteria in a carbon-deficit state. In other words, more energy is required to rehydrate and gear up the photosynthetic apparatus than is produced before desiccation inevitably sets in. This is not to suggest that this happens every time, as Cable and Huxman (2004) identified cyanobacteria crusts that produced soil carbon gain following small pulse events. From a species survival strategy, the organisms must rely on the moderate to heavy pulses to allow metabolic gains. These pulses are infrequent and are commonly associated with storm activity. Storms are usually short, high-intensity events, with high solar radiation rapidly returning, reducing the productivity time for the soil cyanobacteria.
Analysis of rainfall events at Diamantina shows that summer rainfall is associated with areas of atmospheric low pressure and troughs. These conditions induce unstable moist air, often producing stormy rainfalls. Storm conditions produce larger rainfall totals in shorter time periods, which often results in the claypan surface rapidly sealing and causing runoff. Rainfall is summer dominant (see Figure 2.3), with 75 percent of rain falling in the spring/summer months. In contrast, winter rainfall is associated with cold fronts bringing smaller rainfall totals, frequently at night and over a longer duration. The differences between these rainfall patterns potentially affect the way in which cyanobacteria could utilize the moisture, not because of the rainfall totals, but rather because of the solar radiation associated with each type of event. Summer storms are short, intense events rapidly returning to high solar radiation conditions. In contrast, frontal rainfall, while delivering smaller rainfall totals, has longer time periods of overcast conditions. In this latter scenario, photoinhibition of the cyanobacteria under high light is less.

A change in precipitation regimes, as predicted from climate-change models, would decrease total rainfall but increase high-intensity pulses in the arid centre of Australia. If this proves to be the case, soil cyanobacteria will be in a detrimental position, with fewer low-light growing events, relying instead on maximizing the low-light ‘windows’ around the high-intensity big pulse events. The frequency of such events will determine the potential outcomes for the
landscape stability. If the frequency of small pulses decreases and larger pulse frequency only increases marginally, the soil cyanobacteria may not maintain production to existing levels. In addition, vascular plants which rely heavily on the larger pulses may be unable to colonise, resulting in greater wind erosion pressure placed on the soil crusts.

7.4 Summary

This chapter examined how the cyanobacterial crusts of LC claypan respond to environmental stimuli. Four questions were posed, and the results of experimentation addressing these questions are summarised below:

**Question 1: What quantity of rainfall is required to initiate growth of the LC claypan crusts?**

The addition of any amount of water resulted in the crust rehydrating. Once the moisture content exceeded four percent volume to weight, a fluorescence increase occurred. A moisture content over 14 percent resulted in sustained PSII activity. These values appear to be consistent with the literature, although it is difficult to directly compare due to the diversity and inconsistency in reporting of water content.

Rainfall is generally viewed as the ultimate limitation to growth, however the results of this study show that simple application of water is not sufficient to guarantee PSII activity.

**Question 2: Do light and nutrients control the growth of cyanobacterial crusts?**

High solar radiation in the field inhibited crust photosynthetic activity, despite the addition of moisture. This photoinhibition was inferred to be related to solar radiation but temperature was not specifically tested and therefore should not be ruled out as a co dependant variable. This would require very careful experimentation in the field to separate these two environmental variables. These results are consistent with those found in the literature for similar species growing on different continents. It appears that the cyanobacteria present at Diamantina have adopted avoidance strategies to cope with photoinhibition. The capacity for these organisms to migrate vertically within the soil profile not only protects them from solar radiation, but also allows them to track moisture gradients within the profile. This migratory capacity needs to be considered when using monitoring techniques which only survey the soil surface, such as fluorescence monitoring and remote sensing.
The addition of nutrients to crust specimens did not alter the response significantly. Despite the perception that aeolian deposition would be a significant source of nutrients, the results were not conclusive. It is highly probably that nutrient responses made by BSC may be species-specific, and in fact continent-specific, depending on the nutrient status of the soil. It would appear that the cyanobacteria crusts of LC claypan are not nutrient limited, suggesting that sufficient nutrients are being derived from the soil.

**Question 3: Does the combination of these parameters relate to common rainfall patterns in the region?**

Despite the specific requirements of cyanobacteria for rainfall at certain solar radiation levels, it appears the organisms are very resilient and opportunistic. A study from the United States (Cable and Huxman, 2004) showed that the crusts were important carbon producers during small rainfall events (2 mm). Analysis of frequently-occurring rainfall patterns at LC claypan showed that small rainfall events dominated the site, with 55 percent of events depositing less than four mm. Importantly though, it was seen that these small rainfall events were generally associated with longer periods of cloud cover, thus maximising the potential growing time. Summer storms produce high-intensity, large quantities of rainfall, but are associated with shorter cloud times resulting in a rapid return of high solar radiation and reducing the growing time of the cyanobacteria.

The ecophysiological requirements of the cyanobacteria pose questions about the long-term stability of the landscape against wind erosion following projected changes in rainfall patterns due to climate change.
Chapter 8. Spatio-temporal Perspectives of Claypan Erodibility

The fundamental building blocks of wind erosion are the processes of sediment entrainment, transport and deposition (e.g. Pye 1987). The impacts on the landscape of wind erosion entrainment and deposition processes have been well documented since the seminal work of Bagnold (1941). However, it was McTainsh’s (1987) model of sediment recycling that provided the first integrated interpretation of these processes in the landscape. McTainsh (1987) identified rivers as the source of vast amounts of fine sediments. These sediments produce the Harmattan dust storms in the most active dust region on earth: the Chad Basin. By linking river systems and wind erosion, McTainsh pioneered a new way of looking at arid geomorphology as a system of sediment recycling and an important ecosystem function. Two decades later, Bullard and McTainsh (2003) identified similar processes in the Lake Eyre Basin to those identified in the Chad Basin. They speculated that the 6.5 million square hectares of river systems flowing into Lake Eyre carry sediment to the internal basin. This freshly-deposited sediment is then entrained and deposited back onto the catchment area. This Australian system represents a sediment recycling process on a massive scale.

Sediment recycling results in a constantly changing soil surface. Floods supply fresh sediment to the claypan surface, having the effect of ‘re-zeroing’ the claypan surface, burying the effects of previous wind erosion activity. Once dry, however, time and climatic variation impact the sediment creating a mosaic of surface types. Chapter 5 characterised the diversity of such surface types, while Chapter 6 used measurements at four field sites to develop a model of the spatial patterns of erodibility across the claypan. What is missing from these models, however, is an understanding of the dynamic nature of the surface types—i.e. how they change through time. The ‘living soils’—the cyanobacteria crusts noted in Chapter 7—were found to be very responsive to changes in climatic stimulus, and therefore change the soil surface layer through time.

Up to this point, this thesis has concentrated on ‘space’ related issues such as the spatial patterning of surface types and erodibility measures of field sites. Understanding erodibility, and hence sediment entrainment, within the claypan
provides important insights into the triggers that occur through time responsible for entrainment, transport and deposition of sediment, and also the crucial triggers of cyanobacterial filament entrainment and possible transportation. At a broad scale, this chapter concentrates on the temporal aspects of erodibility. It seeks to identify how different surface types react to variable weather conditions through time to produce a dynamic claypan surface. I have approached this section by discussing a series of questions. Evidence to support the discussion is based on ten years’ field experience working in the Channel Country, and more recently, in the context of this PhD, on the Lake Constance claypan. Where possible, additional empirical evidence is introduced to investigate the likelihood of cyanobacterial crust propagules being entrained and transported within the claypan.

8.1 Crust continuum model

Spatial heterogeneity of crust types across the claypan surface has shown to be large (Chapter 5). What Chapter 5 and the erodibility maps in Chapter 6 do not show is that they change through time. Sometimes the change in crust form is subtle, for example further development of a cyanobacteria crust; or sometimes it can be dramatic, as in the case after a flood event. I propose that the first step in understanding these temporal changes is to develop understanding of the relationships between crust forms. If a greater understanding of crust formation processes is made then there is a greater chance that prediction of its predisposition to erode will follow. Some processes, such as climate, occur over large spatial scales, while soil characteristics vary on much smaller scales. The development of a crust can be described as a function of what lives there, how long they have been there, and how they cope with change.

What lives there?

The distinction between a physical and a biological crust is based entirely the biological organisms that inhabit the soil surface. If the physical conditions are not conducive for biological colonisation, a physical crust will prevail. The species diversity of the biological crust is determined by time, sediment supply, climatic conditions, disturbance and, ultimately, a species ecological range. As discussed in Chapter 6, the erodibility of a crust is in part determined by soil properties such as
surface roughness, soil aggregation and crust strength. These properties and others are determined by what lives there. Species composition does not have to be complex for a BSC to achieve pinnacle status. The BSC of Utah consists of mosses and lichens forming undulating plains with microtopography of up to 80 mm high (St Clair et al., 1993). BSC of the Kalahari plains (Thomas and Dougill, 2006) and Central Australia (Strong unpubl. data) consist of cyanobacterial crusts with up to three or four species. On each site the organisms have expanded to their ecological potential, imparting strength to the soil surface.

**How long have they been there?**

The age of a BSC provides a good indication of its resilience to stress. Well-established BSCs have generally endured a range of climatic extremes, both deleterious and beneficial (e.g. dune and sand sheet crusts). BSCs that are being established are vulnerable to climatic conditions. Unconducive conditions could potentially result in a retreat along the crust continuum back to a physical crust. The washout site of this study is an example. Well-established crusts provide a stronger layer, have a greater surface roughness and ameliorate the soil properties, enabling the growth of vegetation. These properties produce a soil surface which has greater resistance to abrasion.

**Can they cope with change?**

The stability of a crust is determined by the vulnerability of a species to disturbance or climatic stress. This is affected by parameters such as:

- how established the organisms are in the environment; and
- the severity of the change.

Both anthropogenic and environmental disturbances impact on the ability of a BSC to survive. Research investigating the response of BSCs to livestock (Rogers and Lange, 1992; Eldridge and Ferris, 1999), recreation vehicles (Webb and Wilshire, 1983) and fire (Johansen et al., 1984) has shown that recovery times vary depending on species composition. The level of protection given to the soil varies not only with species composition, but also the intensity of a disturbance.
These three simple questions essentially define the links between the biological and physical ends of the crust continuum model. The model provided in Figure 8.1 indicates that time is the controlling feature of crusts. In the arid northern areas of Australia, where cyanobacteria dominate, surface crusts will encounter a great array of disturbances and climatic variation. Mechanical disturbance of a surface can modify the type of physical crust or it can destroy part of the biological community, altering the type of BSC which remains. Climate is a very important controlling element. Frequency and quantity of rainfall and flooding are pivotal controlling factors. Not only are they essential for sustaining growth directly, but they indirectly affect the crusts through processes such as salinity and sedimentation.

![Figure 8.1 The crust continuum model of geomorphic settings and crust formation](image)

The elements of time will alter the type of physical crust which is produced. For example, changes in rainfall or flooding frequency will alter the salinity levels, modifying structural crusts into depositional crusts. Biological crusts start with simple communities, generally one cyanobacterial species. If the elements of time are favourable, the crust will become more complex, increasing species richness and surface roughness and providing an improved soil microhabitat conducive for
vegetation growth. To this extent, this biological continuum can be represented as an isosceles triangle. The acute angle is at the intersection between being biological or physical in form. The elements of time determine the direction of crust formation. One side of the triangle represents surface roughness, while the other side represents vegetation cover. Both sides become more complex as you approach the base of the triangle which represents the pinnacle stage of crust development: the greatest species richness offering the greatest soil stability for that particular geographical location.

8.2 Weather impacts on erodibility

The crust continuum model proposes that crusts develop along a continuum ranging from physical to biological in form. The positioning of a crust along this continuum is a function of time with the impacts of climate and disturbances controlling the direction of crust development. It is suggested that the current day morphology of a crust is a culmination of a large number of possible impacts such as rainfall and flooding, soil salinity, and the intensity and frequency of a range of disturbances. In an attempt to explore the temporally dynamic nature of surface types on the claypan, I will discuss the effects of only one ‘disturbance’ factor—water—on the rates of wind erosion and soil surface erodibility.

8.2.1 When does wind erosion occur?

In order to explore the impacts of water on the rates of wind erosion, it is important to outline when wind erosion is known to occur. Wind erosion is highly episodic, with the same claypan yielding a range of sediment fluxes over a matter of weeks (Nickling et al., 1999; McTainsh et al., 1999; Hupy, 2004; Reheis, 2006). In a long-term erodibility study of the Lake Constance claypan, vastly different flux rates were measured both within and between years (McTainsh et al., 1999). The addition of water, either in the form of rain or flooding, has traditionally been considered to decrease the erodibility of a soil surface with respect to wind erosion (Shao et al., 1996). The increases in moisture content, sealing and vegetation cover are thought to protect the soil. However, the relationship between wind erosion and rainfall is not so unidirectional. In the western USA, Reheis and Kihl (1995) found that dust deposition rates increased during high precipitation years. This may reflect an obvious ‘washout’ of the atmosphere, but it may also reflect increased entrainment rates at local source
claypans. From 1994 to 1996, a slight decrease in erodibility (21 percent) on the Lake Constance claypan following an increase in rainfall was not, however, accompanied by an increase in vegetation cover as expected (McTainsh *et al.*, 1999). Using fine-scale weekly data collection, McTainsh *et al.*, (1999) identified that small rainfall events (< 10 mm) increased erodibility, while large rainfall events (> 50 mm) reduced erodibility. While the authors stressed that these trends were tentative, they hinted at significant relationships. The largest dust flux events in 1995 and 1997 were both preceded by small rainfall events. Such trends have continued to occur at Lake Constance claypan for at least a decade.

These trends are not unique to Australia, with a 16 year dust deposition study in America finding that high dust fluxes occurred in years of both drought and above-average rainfall (Reheis 2006). Working on different playa surfaces, and interpreting only bi-annual data, Reheis (2006) identified that rainfall chiefly altered the surface texture, which in turn supplied fresh sediment for entrainment. High-intensity rainfall that created overland flow was seen as one process that produced dust, once the surface dried.

### 8.2.2 How can rainfall increase erodibility?

A number of physical explanations as to how rainfall increases erodibility exist, and these generally involve some form of surface disturbance. Raindrop impact is commonly viewed as a surface disturbance. Large raindrops up to 6 mm in diameter have sufficient momentum and mass to cause pitting, compaction and redistribution of sediment across the landscape (Johnson and Gordon, 1988; Kidron and Pick, 2000). The majority of raindrop impact studies are restricted in scope to effects on water erosion. Raindrop impact, in this classic water-erosion sense, focuses on the physical detachment followed by the associated transportation of these sediments away from the site via overland flow (Moss and Green, 1983). However, raindrop impact can alter the surface roughness, change the surface type and redistribute loose erodible material. All of these are important attributes known to change the soil’s erodibility to wind. Despite this realisation, limited wind erodibility work focuses on raindrop impacts. Even the wind tunnel work of Erpul *et al.*, (1998) was focused on the effects that wind speed had on the raindrop size distribution, rain impact angle, rain drop energy and, ultimately, the effect on the surface flow transport of the eroded...
sediments. Limited discussion has been raised to the potential impact that rainfall has on altering the erodibility of a soil surface to wind erosion.

Observational data collected from the Lake Constance claypan provides some clues to the likely effect of rain drops on reorganising the soil surface and potentially creating available sediment for entrainment. Examination of a cyanobacterial crusted site on the homestead claypan following 5.6 mm of rainfall (Figure 8.2a) shows that the fine erodible material lying on the crust surface has been reorganised into small (< 1 mm height) ridges forming circular patterns. A bare sand dune surface following 7.6 mm of rainfall displays clear pitting and ridging of particles as a result of raindrop impact (Figure 8.2b). Following 2 mm of rainfall, parts of the homestead claypan produced a detailed lumpy surface with micro-topography reaching heights of 5–10 mm (Figure 8.2c). Once dry, all of these surface modifications have the potential to increase erodibility.
Another physical mechanism by which rainfall can alter the erodibility of the claypan is surface sealing induced by saline conditions. Once sealed, the surfaces will pond water, potentially forming a range of physical crusts. In situations where there are loose, erodible sediments lying on the surface before the wetting event, ripples can form through the action of wind and waves. Figure 8.3a shows an example of ripple formation while the surface is still under water. After drying, these surfaces have increased roughness, but through time the weak physical crusts rapidly breakdown.
with saltation impact. Such ripple formations then provide a very productive saltation source area for fine sediments (Figure 8.3b).

Figure 8.3 a) Formation of mini sediment ripples created by wind action while homestead claypan was under flood water. b) Subsequent erosion of the mini ripples upon drying.

A third example of a physical change that might increase erodibility is based on observational and empirical measurements of a single rainfall event and associated wind erosion phenomena from the Lake Constance claypan. In this case, a very high sediment flux event (143 348 g/m/wk) from LC claypan in October 1998 was initially viewed as an anomaly. On closer inspection of collected sediments, a high proportion of clay curls was revealed. Clay curls are depositional crusts which can form from the ponding of water. The meteorological records revealed a small rainfall event of 7 mm falling on 12 October 1998. The weekly sediment collection from dust traps placed across LC claypan occurred on the same day, but before the rainfall, and identified a small but average sediment flux rate (3016 g/m/wk). Sunny conditions following the rain rapidly turned the large ponded areas into masses of clay curls. The sediment flux increased 18 fold over the following week and dry sieve analysis of the collected
sediment revealed that 40 percent consisted of clay curl fragments greater than 2.8 mm diameter (Figure 8.4).

Climate was the impetus for surface change in this event, ultimately resulting in increased erodibility of the claypan. Rainfall, sunshine and wind all participated in altering surface conditions, changing the nature of the physical crust form. Strong north-westerly winds during the week ending 19 October 1998 relocated the large clay curls (aggregates of clay deposited as thin layers) to the claypan margins. These aggregates were too large to be held aloft and therefore remained within the boundaries of the claypan. Instead, the curls acted like saltation material bouncing or hopping across the claypan, chipping fragments from themselves as they migrated. Clay curls were deposited in the lee zone of any obstruction such as vegetation, rocks or posts (Figure 8.5). During the following week (19 to 25 October 1998), the wind
direction changed and the deposits of clay curls were entrained and blown across the claypan in another direction (Figure 8.6). As they saltated back across the claypan the clay curls reduced in size further, increasing the proportion of fine sediments collected. Sieve analysis revealed that by the end of week three (25 October 1998) the coarser-sized curls had broken down to smaller fractions, with the 125 µm size class being dominant (Figure 8.4). There was 7.2 mm of rainfall on 26 October 1998, with subsequent destruction of the remaining clay curls.

Figure 8.5 Deposition of clay curls behind vegetation.
Three important points can be noted from this event:

- First is the strong connection between weather and erodibility. In this case, rainfall was instrumental in forming a physical crust.

- Second, the clay curls moved as aggregates. Because of their size, the curls were initially restricted to movement within the claypan, but subsequent remobilisation decreased the average curl size, thus increasing their likelihood of being removed from the claypan. The ability of wind to move sediment as aggregates offers a mechanism by which cyanobacteria could be moved. Transport within aggregates would provide greater physiological protection and perhaps greater colonisation opportunities. This hypothesis is returned to later.

- Finally, the formation of clay curls would appear to be a mechanism by which small rainfall events might initiate high erodibility as predicted by McTainsh et al., (1999).

Three ways in which rainfall might alter the soil surface and increase erodibility have been presented: rain drop impact, ripple formation and clay curl production. All three not only modify the type of physical crust present, but also frequently break down the crust to produce a source of loose erodible material. Chapter 6 identified that
cyanobacterial crusts have enough surface roughness to store loose erodible material. If surface roughness is an eco-physiological response of cyanobacterial crusts to rainfall, then it would stand to reason that certain changes in surface roughness of cyanobacteria crusts might similarly increase erodibility.

8.2.3 Cyanobacterial crusts and rainfall
Cyanobacteria have a metabolic requirement for water, usually delivered in the form of rainfall in arid Australia. They also require light. But it is the interaction of these two growing requirements that determines the behaviour of the crust. Field observations support the experimental findings of Chapter 7 indicating that the duration of soil surface greening is related to rainfall quantity and the amount of solar radiation received after the rainfall event. For example, 11 rainfall events occurred between 10 and 26 April 2000, with the largest amount, 82 mm, falling on 12 April 2000. This large event initiated mass ‘greening’ of the cyanobacterial crusts as Microcoleus sp. moved to the surface (Figure 8.7a). The following two weeks provided ideal growing conditions as showers delivered another 50 mm of rain across nine individual events and ongoing overcast conditions prevented photoinhibition in the crusts. The rainfall totals of these events varied between 0.2 mm to 26.8 mm. This is reflected in the photo time series (Figure 8.7b–e). The smallest rainfall event, receiving only 0.2 mm (Figure 8.7d), noticeably produced the least surface greening as a result of increased duration of solar radiation. Following large amounts of rainfall, the cyanobacteria frequently reside on the soil surface, retreating briefly during the periods of highest solar radiation.
Figure 8.7 The variable surface greening of cyanobacterial crusts following various rainfall events: a) following 82 mm of rainfall; b) following 5.6 mm of rainfall; c) following 26.8 mm of rainfall; d) following 0.2 mm of rainfall; e) following 11 mm of rainfall

An even more dramatic example of this is the comparison of two small rainfall events, one on 21 December 2000, the other on 5 January 2001. Both events experienced similar conditions: the December event delivered 2 mm of rainfall preceded by 4 days of no rainfall while the January event delivered 2.4 mm of rainfall preceded by 8 days of no rainfall. Figure 8.8a shows little sign of cyanobacterial growth in the December event while intense greening occurred during the January event (Figure 8.8 and Figure 8.1b). The time of day in which the rainfall fell is crucial for metabolic utilization by the cyanobacteria. The event on 21 December 2000 was a short-duration storm.
occurring in early afternoon. Early summer storms allow for high solar radiation to return before dusk, which is often around 1930h. Rainfall on 5 January 2001 was a late-evening storm thus allowing the soil to stay moist overnight and allowing a photosynthetic response from the cyanobacteria at dawn. Again, the variable response of cyanobacterial growth to the interaction between hydration and light is emphasised, in particular the effect of the combination of these conditions on the physical structure of the crust.

Figure 8.8 Variable responses of cyanobacteria to similar rainfall quantities reflecting the importance of climatic preconditioning.

8.2.4 Cyanoheave
The dramatic physiological responses of biological crusts to rainfall raises questions as to whether the movement of cyanobacteria to the soil surface can create a disturbance that might increase erodibility. If we consider the physiology of
cyanobacterial crusts during rapid growth, it is plausible to suggest that this may
displace sediment in the same way raindrops can. The large mobile cyanobacteria are
found to depths of up to 10 mm and the larger species, particularly *Microcoleous* sp.
frequently migrate to the soil surface post hydration. Hydration results in the
cyanobacterial filaments imbibing moisture, increasing in volume and then physically
growing filament length. As the cyanobacteria hydrate and move to the soil surface, a
degree of particle disruption occurs. Even if a proportion of the cyanobacteria move in
pre existing sheaths, alternating hydration cycles has the potential to disrupt particle
packing. We can conceptualise a process not dissimilar to frost heave, and thus term
this potential cyanobacterial process 'cyanoheave’. Frost heave describes the
phenomenon whereby soil freezing causes upward soil surface motion through either
the development of lenses (Fowler and Noon, 1997) or ice needles (Matsuoka, 1998).
In either case, soil can be moved, ranging from a few grains lifted at the surface to the
lifting of a soil layer several centimetres thick. The spatial scale of a single grain at
which needle ice forms is potentially comparable to the scale at which cyanobacteria
move through the soil.

The proposed cyanoheave process could occur each time a dehydrated crust absorbs
water. There is sufficient evidence to suggest that organisms increase in volume and
length in a short period of time in response to hydration. Campbell (1979) and Wang
*et al.*, (1981) found that soil cyanobacteria could absorb up to 12 times their dry
weight, increasing their volume up to 10 times. Considering that these phenomenal
growth rates occur within the top 10 mm, and most commonly in the top 4 mm
(Garcia-Pichel and Belnap, 1996) of the soil surface, it is plausible that soil particles
within the crust profile will be displaced.

In a first step toward demonstrating the feasibility of the cyanoheave concept, a
microscopic analysis of rehydrated LC claypan crusts was performed to examine the
effects of filament expansion. A sample was hydrated while on the microscope stage
and filmed for one minute. Observations revealed that growth of cyanobacterial
filaments could certainly move soil particles. Frames taken each 30 seconds from the
recorded microscope view of a *Microcoleous* sp. expanding with the addition of water
are presented in Figure 8.9. As the filament expanded in size, it pushed larger quartz
grains away. These images represent the activation of only one filament. If this effect
is multiplied up by the biomass found within the soil surface, there is potential for significant soil surface disruption.

Figure 8.9 Hydration of soil cyanobacteria as seen through a microscope at x100. A frame every thirty seconds has been displayed highlighting the expansion of the filament and the movement of the soil grains. Scale bar = 50 µm.

Given the experimentally-determined response of cyanobacteria to hydration, light and potentially temperature cyanoheave is likely to be highly dependant on these same conditions. First, let’s consider moderate to heavy rainfall events. As demonstrated by field observations of cyanobacterial growth described above, prolonged rainfall, with associated low light conditions, are optimal for the growth of biological crusts. Soil stability under this scenario is promoted via physical entanglement of the soil particles with filaments and/or the binding of soil particles via secretion of polysaccharide gels.
Now consider the scenario of short rainfall events. We have experimentally
determined that wetting of the soil is sufficient to start PSII activity. But short rainfall
events provide insufficient moisture to maintain growth. The process of physical
entanglement and polysaccharide secretion does not occur instantaneously, requiring
time periods not supported by small rain events. Instead, the cyanobacteria are
metabolically ‘awoken’, and respond by expanding in size, gliding to the soil surface
and then retreating back into their sheaths below the soil surface as the soil dries with
the declining moisture front (Figure 8.10) to avoid damage from UV-rays (Tchan and
Whitehouse, 1953; Dor and Danin, 1996). During the rapid expansion of the
cyanobacteria, the soil surface is micro-heaved as the filaments are forced to retreat,
leaving the soil surface slightly expanded to a puffy condition with a greater number
of micro-voids. This ‘puffy’ condition would then make the surface more vulnerable
to saltation impact resulting in potentially greater sediment loss.

![Figure 8.10 Schematic of Cyanoheave. Large rainfall events initiate cyanobacteria growth
and soil stability, while small rain events stimulate cyanobacteria growth but are
insufficient to sustain growth.](image)

From a wind erosion perspective, any modification to the soil surface increases the
risk of sediment loss. Regardless of whether the surface modification comes in the
form of raindrop impact, disturbance or cyanoheave, either macro or micro alterations
ensure the crust is made vulnerable. Loose sediments provide a source of saltation
material while puffiness decreases its resistance to saltation bombardment. Exposing a
crusted surface to saltation will ultimately lead to an increase in sediment loss and potential cyanobacteria entrainment.

### 8.3 Cyanobacteria redistribution within the claypan

The effect of water as a ‘disturbance’ factor has been shown in section 8.2 to modify the erodibility of a claypan surface through time. The addition of water in the form of rain or floods can change the surface features through physical or biological processes. Such changes result in the crust types changing according to the crust continuum model. Exploring the effect of water on the claypan is perhaps conceptually easy as there is a ‘hydration’ event, followed by a crust response and ultimately a change in the claypan surface features. Potentially a little more conceptually difficult to appreciate is the impact that wind can have as a ‘disturbance’ factor. Whilst this thesis is discussing the erodibility of a claypan surface to wind, it is important to acknowledge that the effect of the wind does not stop at the wind erosion process of entrainment. As entrainment is a point in time, but through time the processes of transport and deposition follow. The following three sections will explore the notion that wind itself acts as a powerful ‘disturbance’ factor, activating crust change as per described in the crust continuum through the processes of transportation and deposition and therefore ultimately contributing to the spatial patterning of crusts across the claypan.

By living in the surface sediments of an arid claypan, the cyanobacteria are guaranteed to experience disturbance from wind. Based on the rates of sediment transport around the claypan, it is plausible that wind erosion can fracture cyanobacteria crusts removing both sediment and cyanobacterial filaments. Sediment transport results in a winnowing of the finer sediments, often creating sediment streamers (Figure 8.11) (Livingstone and Warren, 1996). It is the aerodynamically smaller and lighter particles that are capable of attaining the greatest heights, forming dust, and being removed from the claypan. The coarse fraction is transported within the boundaries of the claypan. When the wind speeds decrease, the transported sediment is deposited, often forming sandy deposits (or small nebkha ~ 300 mm high). It is at this point that the all-important transport mechanism opens up a new colonisation phase on the claypan. It has been suggested that this deposited sediment
is enriched with nutrients and organic matter (Tongway and Ludwig, 1994), and I propose that it is also enriched with micro-organisms.

![Figure 8.11 Sediment streamers blowing away from camera.](image)

### 8.4 Cyanobacteria entrainment, transportation and deposition within the claypan

If cyanobacteria are being entrained, transported and deposited within the claypan, it is essential to find filaments in the atmosphere. To this end, a range of sediments were analysed for chlorophyll $a$ and cellular counts with the aid of epi-fluorescence microscopy. To determine whether cyanobacteria were capable of being entrained, samples were analysed from micro wind tunnel collections (See section 6.2.4). These sediments were collected on filter papers and represented wind speeds ranging from 6 to 13 m/s. To determine whether cyanobacteria were being transported, archived samples collected with wind vane samplers (WVSs), the semi-isokinetic tower, and deposition traps over the past 8 years were analysed. The age of the samples, coupled with the opportunistic nature of collection, result in a sampling that is not ideal.
Despite sampling limitations, cyanobacteria were found in all the wind eroded sediments collected from the saltation and suspension components. Saltation sediments were collected with the MWT and the lowest WVS height. Suspension sediments were collected with the two-metre WVS and the semi-isokinetic tower. The highest cell counts—greater than 110,000 cells per gram of sediment—were found in the suspension component. The saltation components had a third of these counts (Figure 8.12). Analysis for chlorophyll $a$ content revealed comparable trends to those measures from the crusts both on LC claypan and claypans throughout western Queensland. Samples collected at 2 and 10 m were of insufficient size to allow chlorophyll analysis.

The greater concentration of filaments in the suspension fraction suggests that the weight and size of the filaments allows for the filaments to be size-selected while in
the air. Such preferential sorting would assist in the transportation of filaments both locally and over longer distances. However, the WVSs are size selective and inefficient at capturing particles smaller than 50 μm (Shao et al., 1993). Filaments collected with the wind tunnel and at 0.02 m with the WVS would be associated with larger sediment masses and potentially cyanobacteria moving as aggregates. While filaments moving as aggregates were noted during light-microscopy examinations, by far the greatest number of filaments were seen individually. The data set was too limited to draw too many conclusions regarding the movement of filaments as aggregates, however there is sufficient evidence in the literature identifying that biological crusts erode as aggregates (McKenna Neuman et al., 1996; Leys and Eldridge, 1998). The dominance of singular filaments found in these samples may imply the breakdown of aggregates either during the saltation phase or while in the air. Once free of their aggregate environment, the filaments would be subjected to buoyancy and size selectivity factors. Alternatively, sample preparation for epi-fluorescent microscopy required serial dilution, a process that may have favoured the sampling of filaments over aggregates.

While the entrainment of filaments has been shown to be possible, there was little evidence of chlorophyll a or cells present in deposition traps. This may reflect small sample sizes, inappropriate sampling strategy or in vivo preservation techniques more than the filaments being deposited. If there is a bias of singular filaments to be transported, it could be assumed that the filaments are more buoyant than an aggregate or group of filaments, and would therefore require calm conditions for deposition to occur.

Although cell counts from the deposition traps were low, counts from the saltation and suspension fraction highlight that cyanobacteria are being entrained and transported within the claypan. This being the case, any small deposits of sediment across the claypan will produce an ideal growing medium of sand, nutrients and filaments. Combined, these three elements produce, in effect, a ‘nursery ground’ for the development of crusts. All that is required is rainfall.
8.5 Nursery ground model

The nursery ground model of colonisation can be used to interpret crust development at a landscape scale within the claypan. The nursery ground model (Figure 8.13) relies on environmental factors to dictate the direction of surface development. Wind is pivotal in providing mechanisms of entrainment, transport and deposition of the ‘nursery growing media’. This media is transported locally within the claypan boundary and deposited at some form of obstacle, such as vegetation, gravel lag or a rough surface. These deposits form the sandy mounds (commonly known as sandy hummocks, coppice or nebkka) rich in sediment, nutrients and filaments. Critical for cyanobacterial development at this point is water, either in the form of rainfall or flooding. Small rain events may induce cyanobacterial growth within the sandy mound, forming thinly-crusted hummocks. Large rain events or floods may redistribute the fine sand across the claypan surface forming a sheet. The cyanobacteria will grow, forming a thin laminar crust overlying the typically blocky clay. Each of these transport and colonisation steps are seen as surface features on the LC claypan and discussed in Chapter 5. The pooled erodibility model map shown in Figure 6.16 predicted small, discrete source areas just like the ones which would be produced by the processes described in the nursery ground model.
An example of the nursery ground model is a description of the washout field site studied in Chapter 6. This field site was initially a cyanobacteria crust with very poor species diversity, suggesting that the crust was at an early successional stage of cyanobacterial development. There was a thin layer of fine sand overlaying the coarsely-aggregated claypan sediment, suggesting that this crust feature was recently created through geomorphic processes. Further investigation of the landscape identified the remains of a large, sandy hummock on the northern side of the crusted area. The hummock had a low salt content, the remains of annual herbs and the ubiquitous cyanobacteria *Microcoleous vaginatus*. The meteorological records indicated that a high-intensity summer storm washed out the sediments of the sandy hummock across an area of 100 m$^2$. The storm also induced slaking in the surrounding sodium-enriched claypan surface. This formed a physical vesicular crust before the sandy hummock sediment was deposited as a thin veneer. Follow-up rainfall enabled
cyanobacteria to colonise this 10 mm-thick veneer. More rainfall was required for the crust to develop into a species-rich biological crust. Instead, insufficient rainfall fell, resulting in the cyanobacteria being weak and susceptible to wind erosion. The surface now had a higher erodibility than if the follow up rain had allowed cyanobacteria development. The surface had produced shifts along the crust continuum in two directions within a matter of months: first towards a biological crust, then back towards a physical crust.

This site also highlights the harshness of the claypan environment, hosting extreme environmental parameters coupled with often-saline sealing soils. These harsh conditions restrict the types of biological crust which can grow, and often result in a swinging from biological to physical crusts through time. Despite this, cyanobacteria have developed many strategies to survive the harsh environment:

- They avoid radiation, actively migrating through the soil profile to seek shelter from UV B (Garcia-Pichel and Belnap, 1996);
- They tolerate extremes in temperature.
- They quickly respond to small rainfalls.

The ecophysiology research discussed in Chapter 7, however, indicated that different quantities of water determine the duration of photosynthetic response by the cyanobacteria. These ecophysiological limitations constrain the use of rainfall. Rainstorm frequency in the Diamantina area shows that the most abundant rainfall occurs as small events (< 4 mm per event). Presumably these small events are characterised by fast evaporation rates and a quick return to high levels of solar radiation. These conditions would result in minimal opportunities for the cyanobacteria to make positive vegetative growth. This lack of growth has the potential to alter soil erodibility.

There are other models which currently describe various aspects of crusts in the landscape. Thomas and Dougill (2007) propose a conceptual model for ‘crust development and burial’ based on similar cyanobacterial crusts in the Kalahari. Their model also acknowledges that crusts develop through time if undisturbed and given sufficient moisture, the complexity and strength of the crust increasing as time passes. Disturbance and raindrop impact is seen as mechanisms for crust regression, leading
to exploitation of the unconsolidated sands beneath the crust by wind erosion. Their model then focuses on the burial of neighbouring crusts. It has been suggested that such burial could cause premature death of the cyanobacteria. But there is evidence to suggest that this may not be a universal phenomenon. Death resulting from burial is known to occur with the non-motile organisms such as lichen and some of the smaller cyanobacteria (Belnap, 2003), but given rainfall, the larger, dominant cyanobacteria will move. Two pertinent research findings support this point. First, biological crusts have been collected and stored in the dark with minimal atmospheric interaction for up to 70 years. The addition of water (Belnap, 2003) results in reinstatement of full metabolic activity and greening of the soil surface. Second, Garcia-Pichel and Pringault (2001) tracked the vertical movement of cyanobacterial in search of moisture, showing that the organisms actively regulated their depth in response to moisture and UV. Timing of rainfall, however, could be crucial for cyanobacteria survival.

An ecological model was described by Bowker et al., (2006) for the Colorado Plateau. Using a nested hierarchical approach for the composition of lichen and moss crusts, their model describes, within a dichotomous key, environmental factors—nutrients and solar positioning (i.e. micro aspect and vegetation)— thought to contribute to the spatial patterning of lichens and mosses at different scales. The strength of the model is that it encompasses five scales, from regional to organism, and uses soil properties as a determinant of lichen/moss growth. The Bowker et al., (2006) model essentially describes the pinnacle stage of crust development based on the perceived controlling elements (such as soil micro-nutrient distribution). Effectively though, these pinnacle stages described by the authors are subjected to the same pressures of climatic and physical disturbances as described by the crust continuum model. Therefore, within each of the 'community suite' boxes described by Bowker et al., the crust continuum model would function. For example, the ultimate composition of mosses and lichens within a vegetative interspace may be determined by the levels of manganese and calcium carbonate, but the continuum of species composition within this micro-site is also determined by variables such as climate and physical disturbances.

It is acknowledged that the nursery ground model is constructed from a hot desert scenario with cyanobacterial crusts that experience rapid fluctuations between the
physical and biological states. The higher-order crusts of cold deserts (such as the Colorado Plateau) potentially have a less dynamic environment, allowing the crusts to develop complex communities. Swings between continuums of crust forms are less obvious in the lichen moss communities as greater intensity disturbances are required to induce change. Catastrophic events, such as major physical disturbances or climate change, may be required to initiate shifts along the crust continuum in these environments.

8.6 Summary

The ways crusts vary through time are crucial to understanding the erodibility of the claypan. Entrainment and transportation of both sediment and cyanobacteria within the claypan boundary influence the development of future crusted surfaces. It has been proposed that crusts develop along a continuum, heavily determined by time. It is through time that climatic variations or physical disturbances induce movement along the continuum. These affect the crusts in logical ways depending on what lives there, how long they have been there and whether they can cope with change. The proposed crust continuum model highlights that both physical and biological crusts are equally affected by such time related pressures. As such, both crust types exist along the same continuum, capable of moving between the two extremes of being physical or biological in nature.

Water is one ‘disturbance’ factor which is experienced on the claypan. Both rainfall and flooding are known to modify the rates of wind erosion and soil surface erodibility. Small amounts of rainfall, in particular, were shown to modify the soil surface erodibility, causing sediment to become available for entrainment. While soil surface erodibility is traditionally thought to be driven only by physical processes such as rain drop impact, clay curl production and soil surface sealing, it is suggested that it can also be increased by small rainfall events that initiate a biological response. While there was little empirical evidence given for the cyanohave hypothesis, the effects of such a mechanism could introduce a new dimension to erodibility studies.

Entrainment and subsequent transportation of sediment is a crucial component to the erodibility of the claypan surface. Collected samples suggest that that cyanobacteria can conceivably be entrained by wind. The highest cell counts were found at the
highest sampling height of 10 m, providing evidence that cyanobacteria are not only entrained, but they are capable of being transported. Transported sediment represents both a saltation source which can abrade other crust surfaces, and also a source of additional sediment available for new crust production. The nursery ground model was proposed as a way of relating sediment movement and deposition across the claypan, highlighting that sediment and propagule cycling within the claypan is essential to the temporal patterning of surface types.

The entrainment of both sediment and cyanobacteria has important implication for the claypan function. Cyanobacteria collected at 10 m have the capacity to be transported distances beyond the boundaries of the claypan. Cyanobacterial filaments have all the characteristics favourable for long range transport: they are small, light and buoyant. Transportation over long distances has potential ecological significance for many ecosystems downwind, as well as contributing to the organic-matter content of Australian dust.
Chapter 9. Future research directions and thesis summary

This thesis has brought together several branches of research in order to better understand the complex physical, chemical and biological interactions that affect erodibility at a variety of scales. Such an approach is rare, making the implications of this study wide ranging for all dryland environments. The overall aim of this project was to understand the effects of surface crusting on the wind erodibility of soils. To achieve this broad aim, five objectives were developed that concentrated on aspects of crusts and erodibility. These objectives were designed to improve understanding of soil surface erodibility to wind in arid, crusted environments.

The first research objective was:

1. To investigate the diversity and spatial distribution of soil-surface types on a claypan of the outer floodplain of the Diamantina River.

From this first objective, three primary conclusions are drawn from the considerable field observation and experimentation conducted.

- The spatial heterogeneity of the surface features described for the LC pan supported a diverse crust types and cover levels. This diversity varied at sub metre increments. Such spatial diversity is beyond the sensitivity of most common measurement or modelling approaches used in wind erosion research.
- Recognizing that an erodible surface is a mixture of physical and biological crusts organised spatially at a micro scale is essential for high resolution erodibility studies.
- Relating the spatial patterning of surface types to sediment flux is a flawed approach, as the positions of the traps do not necessarily reflect the erodibility of the surface type.

Having identified in objective one that the spatial heterogeneity of crusts was greater then the analytical sensitivity of wind erosion monitoring tools commonly used, the second objective of the study was:
2. To develop appropriate methodologies for measuring the wind erodibility of small patches of variable soil surfaces.

To meet this objective, a specialised “Micro Wind Tunnel” (MWT) was developed and field tested. Two conclusions can be drawn from the development and extensive field testing of the Micro Wind Tunnel.

- The MWT provided a reliable and practical solution to providing a relative measure of erodibility between different crust types. The MWT successfully provided laminar horizontal airflow with and without added saltation material, to specific crust types. Importantly, the size of the MWT was appropriate to the spatial heterogeneity of crust types.
- The cross section dimensions of the MWT limit the development of log normal profiles preventing extrapolation of the measured values to 10 m. A mathematical approach to this issue was discussed and appears to be a plausible alternative solution.

Having successfully developed a measurement technique which was capable of dealing with the high spatial heterogeneity of crust features, the third research objective could be explored:

3. To determine the erodibility of different soil-surface types on a claypan.

A number of research findings from this part of the study provide fundamental insights into how future wind erosion researchers should look at soil surface erodibility. The four critical findings include:

- The quantity of loose erodible material (LEM) on the soil surface appears to be an important indicator of erodibility. Surfaces with the highest LEM resulted in higher erodibility measures.
- Biological crusts increased surface roughness resulting in increased storage capacity of LEM. The higher LEM loads resulted in higher measures of erodibility.
The higher erodibility finding contrasted with pre analysis expectations and the international literature, highlighting the role of surface roughness.

- Single measure field studies of soil erodibility may ultimately give false interpretations.
- The characteristics underlying erodibility measures interact to create the ultimate erodibility of a soil surface. Soil particle size underpins the potential erodibility of a surface, while the quantity of LEM exacerbates the effect of surface properties such as strength, number of cracks and quantity of biological material.

Cyanobacteria crusts feature strongly in claypan erodibility. A significant property of these crusts is that they are living organisms, responding to environmental conditions. Understanding these responses by cyanobacteria crusts underpinned research objective four:

4 To improve understanding of cyanobacteria response to fundamental environmental factors, including:
   hydration (i.e. rainfall)
   light (i.e. solar radiation); and
   nutrients.

The ecophysiology of the cyanobacteria crusts responded to different environmental conditions. A summary of these findings are listed below:

- The quantity of rainfall determined the duration of PSII activity. The simple application of water was not sufficient to produce metabolic activity.
- High solar radiation in the field inhibited cyanobacteria crust PSII activity, despite the addition of moisture.
- It would appear that the cyanobacteria crusts of LC claypan are not nutrient limited, suggesting that sufficient nutrients are being derived from the soil. But this result was not conclusive
• The capacity of some cyanobacteria species to migrate deeper into the soil profile needs to be considered when using monitoring techniques which only survey the soil surface, such as fluorescence monitoring and remote sensing.

• The ecophysiological requirements of the cyanobacteria pose questions about the long-term stability of the landscape subjected to wind erosion under projected changes in rainfall as a result of predicted future climate change.

The impact of these biological processes on the geomorphology of the surrounding soils demonstrates that cyanobacteria crusts may have an important function in wind erosion. How cyanobacteria crusts might function in an arid environment in a way that alters geomorphic processes made up the fifth objective of the study as follows.

5. To identify how different surface types react to variable weather conditions through time to produce a dynamic claypan surface.

This objective extended the research from simple measurements to understanding processes and building models of crust processes in the geomorphic landscape. Major conclusions for this research objective include:

• Both physical and biological crusts are affected by time related pressures. The type of crust present on the soil surface is a time dependant feature. To this end, both physical and biological crust types exist along the same continuum and are capable of moving between the two.

• Addition of moisture, either through rainfall or flooding, can increase the rates of wind erosion. Although traditionally considered purely a physical impact, the concept of cyanoheave was developed to describe a biological process capable of modifying soil erodibility.

• Cyanobacteria filaments can be entrained and relocated locally on a claypan. This can form the primary basis of new areas of cyanobacteria colonisation. In effect this ‘seed’ stock of biological material is deposited along with sediment and nutrients.
• Cyanobacteria filaments can be transported by wind. Transportation over long distances has potential ecological significance for many ecosystems downwind, as well as contributing to the organic-matter content of Australian dust.

The overall outcome of these five objectives is a thesis which has managed to explore the spatial, temporal implications of crusted surfaces to wind erosion. This thesis has focused on Australia but the importance of the work spreads across the globe to all drylands. All hot deserts of the world have cyanobacteria crusts, wind erosion and erodibility issues to understand. Understanding biological crust formation and how it affects erodibility is critical as it has implications to geomorphic, ecological and climate functions. Climate change is an important issue at present and whilst this thesis only touched on the subject many of the findings have direct implications. For example determining when the cyanobacteria are active, making carbon gains and when making carbon losses will have significant impact on the survival of the organism in the environment and ultimately impact on the erodibility of the soil. So too will understanding the relationship between rainfall patterns and cyanobacteria response. Such responses have implications for soil carbon, CO$_2$ fluxes and N balances. Considering the projected changes in rainfall patterns across the drylands of the world, understanding the implications of these nutrient balances is critical.

### 9.1 Future Research Directions

These research conclusions highlight crusts as important surface features controlling the erodibility of the soil. Of the diverse crust forms, cyanobacteria crusts represent an important and unique surface feature because they are living and responsive to changing environmental conditions. This results in soil surfaces which change through time as well as space. Understanding of the geomorphic implication of such changes remains in its infancy. Until now cyanobacteria crust research in Australia has focussed on the ecological function of the organisms. However it is their impact on geomorphic function that may provide the key to greater understanding of ecological function.

Along with geomorphic and ecological research potential of crust research there is perhaps a sense of urgency. Increasing knowledge of enhanced climatic change has
brought attention to how wind erosion will alter the global climate budget. This reinforces the necessity to maintain a soil surface crust layer if soil erosion is to be minimised. While this thesis has demonstrated cyanobacteria crusts have a complex but important role in the soils erodibility it has revealed a number of research questions that remain to be addressed in the future.

I will discuss a number of future research directions which I perceive will enhance both the geomorphic and ecological understanding of cyanobacteria crusts in Australia. The future research directions will be discussed in the following categories

- Identification and distribution
- Monitoring methods
- Erodibility
- Ecological function and climate change
- Geomorphic function and climate change

**Identification and distribution**

Knowledge of the distribution of cyanobacteria crusts throughout Australia is limited. There microscopic size and measurement difficulties results in field researchers simply overlooking them. However personal field observations have found them throughout much of the arid and semi-arid of Australia. In light of the finding in this thesis, such a wide spread distribution implies that the cyanobacteria crusts have a significant impact on continental wind erosion rates. Improved knowledge of the distribution of the cyanobacteria would assist in local, regional and continental mapping of wind erosion.

Not only is it the distribution of cyanobacteria crust that is interesting, but it is the community structure that exists at particular places in the landscape. For example the Simpson Desert, one of Australia’s largest dust emitting dunefields is dominated by cyanobacterial crusts. The varied dune surfaces throughout the desert possess a diversity of crust forms representing a variety of cyanobacteria species. Having knowledge of different cyanobacteria present at micro scales will improve ecological, geomorphic and pedological understanding. Recent taxonomic classification based on
genetic techniques has enabled rapid identification of a number of species, but these techniques need to be more accessible if a greater range of species are to be identified.

**Monitoring methods**

Many techniques exist for measuring cyanobacteria crusts and the PAM’s used in this thesis are only but one method which poses opportunities. There are a number of studies which have successfully used remote sensing techniques on BSC. Lichens were mapped in the Namib Desert using satellite sensors (Wessels and Van Vuuren, 1996), cyanobacteria on dunes in the Negev (Karnieli, 1997), and the effect of wetting of cyanobacteria both in Israel (Karnieli *et al*., 1999) and Australia (O’Neil, 1994). This small but diverse range of research suggests that remote sensing techniques are poised to provide valuable data in the future.

A land based remote sensor was trialled for this thesis in an attempt to characterise the metabolic response of cyanobacteria to hydration. This technique was extremely easy to use in the field, with rapid assessments able to be made using a compact instrument. Two deficiencies made this method unsuitable for this study. First, interpretation of the data proved to be quite difficult requiring an understanding of mineralogical properties of the soil, and areas between crusts. Interpreting the output highlighted my lack of understanding of the technique and importantly absence of advice to interpret it. Second, sampling using the radiometer was only made opportunistically in order to better ascertain its suitability for this study. Unfortunately this data was unable to be processed to the level suitable for this thesis and therefore the results were not included.

Although the results are not reported here remote sensing proves to provide a rapid relatively cheap soil surface assessment technique. Much experimental work will be necessary in order to account for the large perturbations in soil reflectance, but once these are conducted remote sensing will be able to be used to investigate process based problems.
**Erodibility**

Wind erosion is an important issue within Australia affecting productivity, rural economies and social health. It therefore requires continued research effort to improve the understanding of the causal mechanisms and downwind effects. Soil surface erodibility as shown in this thesis is a very complex issue is often treated at a cursory level. It is important therefore to expand the understanding by conducting more erodibility studies akin to this thesis in order to improve basic understanding of erodibility. The suite of erodibility measures used in this thesis provides a strong basis to measure the diversity of surface forms. As it is this diversity of crust forms that contributes to erodibility complexity the greater the understanding gained by conducting more studies will improve understanding.

Further development of the Micro Wind Tunnel, to accommodate for the small cross sectional area, would be important to ensure that it is viewed as a legitimate measurement technique for wind erosion measurement. It is important that aeolian geomorphologists acknowledge that it is the small scale subtleties of soil surfaces which generate sediment concentration. Large scale tunnels and models simply smooth these variations out.

Cyanobacteria crusts were shown in chapter 6 to alter the surface roughness increasing the storage of loose erodible material. It is important to identify to what extent these crusts can act as dust traps. From an ecological perspective, actively capturing dust will enhance nutrient availability. From a geomorphic perspective, the addition of small soil particles has the capacity to infill existing larger soil particles forming a stronger crust.

**Ecological function and climate change**

The ecophysiology studies in this thesis were a first step in understanding cyanobacteria crust process. They have shown though that;

- ecological and environmental relationships are very complex
- ecological responses impact on geomorphological function of the soil surface
- field observations pose great challenges.
Future research should enhance the understanding of field responses to environmental triggers. In situ rainfall responses will increase the knowledge of both biological and geomorphic processes. With correct field equipment, the cyanoheave hypothesis can be explored, improving understanding of how soils behave post rainfall. The effect of both quantity and time since rainfall is essential knowledge required to advance the understanding of erodibility. Field monitoring will improve understanding of cyanobacteria crust behaviour which will ultimately allow for predictions of how the organisms will cope with changing climate.

Geomorphic function and climate change
The physical response of the cyanobacteria to environmental change is a complex issue affecting the geomorphology in many ways. In order to expand understanding a number of topics need to be explored. A few of these include:

• What is the relationship of physical and biological crusts in space and time? At what temporal scales do environmental triggers activate movement along the crust continuum?

• What effect does flooding have on the growth of cyanobacteria crusts? Does the influx of alluvial sediment and salt alter the growth rates?

• What role do cyanobacteria play in the rehabilitation of saline claypans?

• Wind erosion models acknowledge that surface conditions contribute to the surface erodibility, but no model has successfully incorporated a crust function. While this thesis has highlighted some of the intricate relationships with time and space it still is a long way from providing input data which accounts for spatial diversity of crusts at a continental scale.

• Finally, returning to the impetus of this thesis, where does all the organic matter found in Australian dust come from? The breakdown of biological crusts releases organic material into the atmosphere. Research needs to be directed towards this organic carbon unknown. How much carbon is in dust, where did it come from and what are the implications to geomorphology, ecology and climate? Sounds like another thesis to me.
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