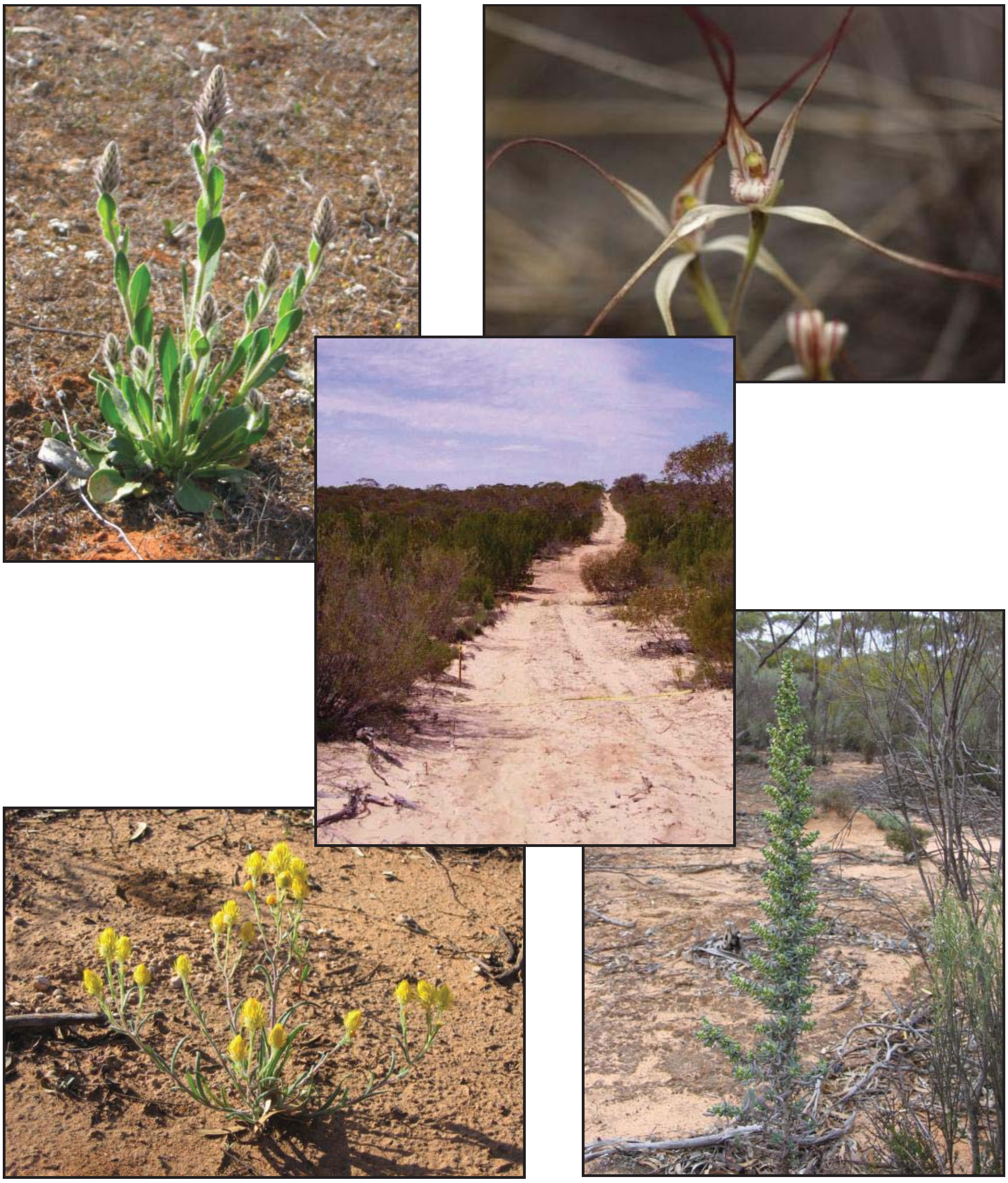
Impact of Mineral Exploration on Ecosystem Characters and Mallee Vegetation of Pinkawillinie Conservation Park, South Australia



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"So erst the Sage with scientific truth
In Grecian temples taught the attentive youth;
With ceaseless change how restless atoms pass
From life to life, a transmigrating mass;
Hoe the same organs, which to day compose
The poisonous henbane, or the fragrant rose,
May with to morrow's sun new forms compile,
Frown in the Hero, in the Beauty smile.
Whence drew the enlighten'd Sage the moral plan,
That man should ever be the friend of man;
Should eye with tenderness all living forms,
His brother-emmets, and his sister-worms."

'The Temple of Nature' by Erasmus Darwin 1731-1802

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Abstract

Recent mineral exploration in South Australia has resulted in many kilometres of tracks cleared in areas of natural vegetation. This study investigates the impact of linear disturbance in formerly pristine mallee vegetation on sand dunes in central Eyre Peninsula.

Paired measurements and samples were taken in the main topographic positions (crest, slope, footslope and swale) along ~400 m of each of three tracks, and closely adjacent undisturbed sites. The tracks were sampled across microtopographic features: centre, wheel rut, shoulder. Measurements of physical characters of soil included: compaction, bulk density, structure, water content, erosion. Chemical characters assessed were: soil nutrients, pH, conductivity, soil carbon (total), along with litter distribution. Vegetation composition and processes were characterised by measuring: soil seedbank emergence, abundance of annual and perennial plants, seed predation by ants, effect of litter on seedling emergence, weed invasion potential, perennial regrowth on the tracks and growth of planted seedlings, soil crust and mycorrhizae.

Soil compaction and bulk density were higher in the swale and wheel rut on the tracks. The swale had higher soil water content for all positions across the tracks and in the undisturbed area, while the wheel rut had more than the other positions. In the swale soil dried out at a similar rate in the wheel rut and undisturbed area, whereas at the crest the wheel rut dried out fastest. After heavy rainfall there was more soil movement down the slope on the tracks than in the undisturbed area. Soil nutrients were higher in the swale, while the wheel rut was more alkaline and less saline than the other positions. Carbon content was slightly higher in the swale, while the amount of litter was no different along the tracks, but was greater in the undisturbed area.

Annual plants were the main emergents from the soil seedbank. More emerged from swale soils from the tracks than from other topographic positions and from undisturbed positions. This pattern was reflected in the distribution of annual plants in the field. The addition of litter had no consistent effect on seedling numbers. Seed removal by ants was independent of topography or disturbance. Tagged perennial plant survival was low at all positions along the tracks over 28 weeks. Overall, fewer dicots died than monocots, particularly at the swale and slope. To assess for weed invasion potential a phytoassay using *Carrichtera annua* resulted in higher growth in swale soils and slightly higher in disturbed soils. Planted seedlings of *Eucalyptus incrassata* reached higher biomass in the undisturbed area in the swale and slope and showed little effect from grazing. Biological crusts were more intact in the undisturbed area and the mycorrhizal content was higher on the tracks.

Clearing of vegetation along access tracks resulted in changes in patterns of transport and retention of materials (water, nutrients, litter, seeds) and this was accentuated by the topographic gradient. Consequently, functioning of the ecosystem changed as was reflected in the vegetation composition in the disturbed area, where there was much less perennial vegetation compared to the undisturbed area.

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Declaration

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give my consent to the copy of my thesis, when deposited in the Library of the University of Adelaide, being available for loan and photocopying.

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Lindy Ann Scott Date

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Dr. Jane Prider advised me on the statistical analysis. Discussions with the rest of my laboratory group contributed to my understanding of the different aspects of research in the biological field. I would also like to thank my colleagues Dr. Renate Faast and Steven Tsang for discussing my trials and tribulations throughout the project.

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§

Chapter 1 Introduction

The semi-arid area of Eyre Peninsula (Figure 1) is part of a former continuum of mallee lands spreading across South Australia between the longitudes 131^0 East and 141^0 East. These areas consist of a number of different mallee communities, which are characterised by several eucalypt species occupying the upper stratum. These trees have the growth habit whereby a number stems shoot from a below ground lignotuber. Due to the low nutrient status of soils and low rainfall these communities are of a sclerophyllous nature. Since European settlement of Australia much of this mallee country has been cleared for agriculture. Mallee can be easily cleared and the soils are suitable for growing crops after artificial fertilisers have been applied (Pickard 1989). This has occurred in Eyre Peninsula, with the agricultural land, however, being marginal due to the semi-arid climate and the infertile soils. Aboriginal people used to go into these thick mallee areas to hunt opportunistically, and while they used the roots of the mallee trees for water, they only inhabited places where water collected and remained on the surface after good rainfalls (Harris 1989). Their extensive and periodic use of fire would have been one of the factors contributing to the creation of the existing ecosystem (Kimber 1983). The areas that have not been cleared by Europeans are those without surface water and those with soils of extremely low nutrient status.

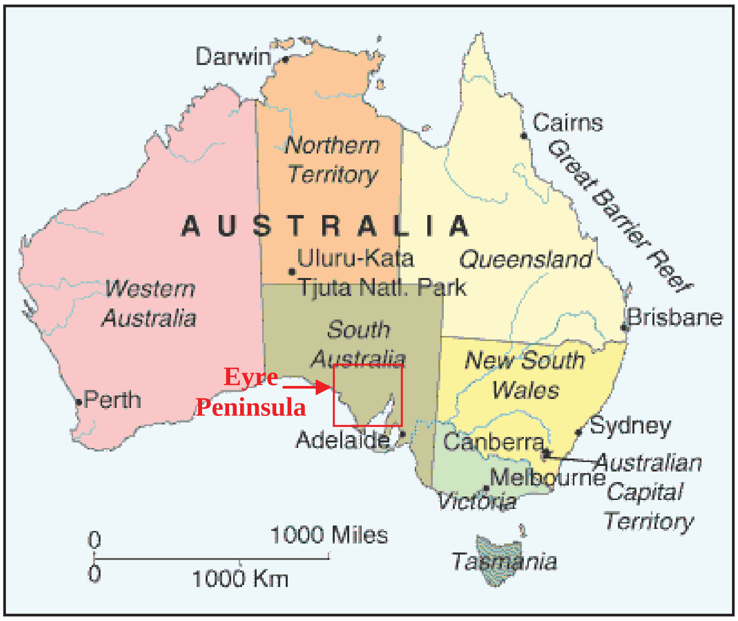

Figure 1.1 Australia, showing the location of Eyre Peninsula

Mineral exploration activities have increased enormously in the past decade with the expenditure in South Australia growing from \$41.7 million in 2003, to \$220.8 million in 2009 (Australian Bureau of Statistics 2010). As part of this expansion there is increasing interest in mineral exploration within conservation areas (PIRSA 2010). It is, therefore, of great importance that the management of these remnant patches maintain, and possibly even enhance, their conservation value. It is also vital that more knowledge of this ecosystem is accumulated and that the impacts of this type of exploration are determined, so as to minimise any potential damage to these areas. Such areas of remnant vegetation, which are intact and, in the main not impacted upon by human activities, have significant value due to the large amount of the surrounding area being cleared for agriculture.

While often no actual mining takes place, exploration for minerals covers large areas in a series of tenements. These tenements consist of grids of cleared access tracks forming internal fragmentation and patches. Linear disturbances together with topography result in the transport of materials occurring within the landscape and there are possible interactions with transport processes occurring within the patches. This has consequences to broad landscape processes extending beyond the tracks (Ludwig *et al.* 2007). Ludwig *et al.* (2007) in their study in north east Australia found that sediment loss at a large scale (0.25 ha hillslopes of about 140 m in length) was greater from the hillslope with large bare patches compared to hillslopes with no bare patches. This loss was 2.5 times greater than that observed at the smaller scale of 0.24 m^2 plots, when comparing those with grass cover with those that were bare (Ludwig *et al.* 2007). The repercussions of these interactions when the disturbance is linear (e.g. the creation of tracks for mineral exploration) are unknown and are an important component to any predictions of sediment loss. There is the added feature of edge effects which are exacerbated with linear clearances resulting in a large edge to interior ratio. For example, Freitas *et al.* (2010) found that the formation of a road network in the Amazon in 1962 had more influence over forest dynamics than the road network formed in 1981, indicating there was a long term effect of roads. The long term effects on forest fragmentation and deforestation depended on topography, land use and road density (Freitas *et al.* 2010). Also in the Amazon the initial clearance resulted in edges that were more exposed and contained lower soil moisture than the interior (Camargo and Kapos 1995). Along these edges there was regrowth of dense vegetation which protected new undergrowth near the edge while soil moisture at the edge was still depleted (Camargo and Kapos 1995).

Over time there was increased environmental heterogeneity further from the edge into the interior resulting in changes in vegetation composition (Camargo and Kapos 1995).

There has been a considerable amount of research conducted on the environmental impacts of mining operations, but much less on the impact of mineral exploration. This is an important gap in our knowledge. Exploration, while perhaps not having as great a disturbance on the land as mining, at least visually, nevertheless affects a much larger area (Allan and Kristensen 1991). The clearance of vegetation along access tracks can result in erosion, different water and nutrient dynamics (Brooks and Lair 2005) and the introduction of weeds (Trombulak and Frissell 2000, Myers and Bazely 2003), feral predators (May and Norton 1996) and non native (Gauthier-Pilters and Dag 1981) and native (Donaldson and Bennett 2004) grazing animals. With these changes the functioning of the ecosystem would be likely to change.

There has been little research conducted on the impact of linear disturbance in semi-arid regions. Pinkawillinie Conservation Park in Eyre Peninsula is an ideal area to explore these impacts, as mineral exploration has been undertaken in an environment which has experienced extremely limited disturbance from anthropogenic activities, since the settlement of Australia. Pinkawillinie Conservation Park was originally held under pastoral lease, but was not significantly stocked due to a lack of permanent surface water. The Buckleboo Stock Route in the south east of the park (Figure 2) was cleared for the droving of stock, but there have been no human settlements within the park boundaries.

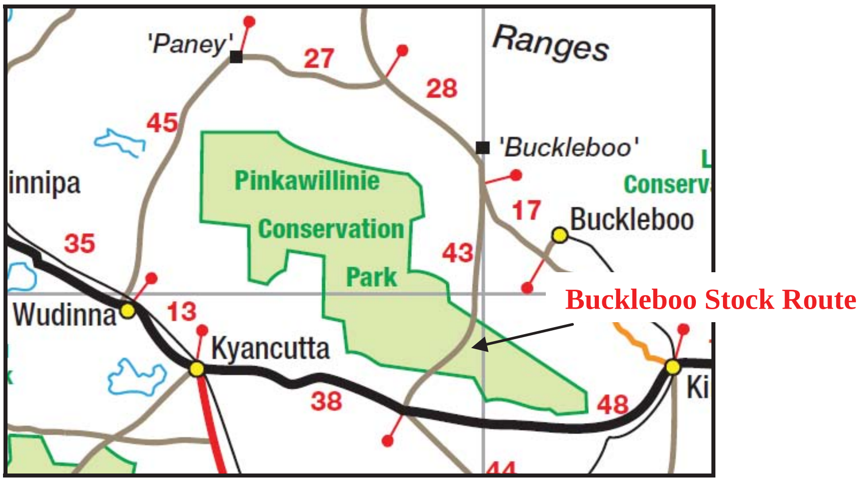

Figure 1.2 Pinkawillinie CP showing Buckleboo Stock Route

a) Natural disturbance

There are many natural types of disturbance, with the intensity and scale, both physical and temporal, affecting the outcome (White and Pickett 1985). The natural disturbance regime in the mallee system in Australia, which mainly consists of a fire regime of relatively frequent, high intensity fires, has resulted in adaptations by the vegetation to withstand the conditions created by this type of disturbance (Specht 1979, Gill 1981a). This is critical to understanding how the system responds to a newly introduced disturbance. The size and frequency of disturbances are characteristics in determining the amount and type of impact (Connell 1978, Denslow 1980b). However, intensity is the most important characteristic in systems relying on buried seeds and resprouting for regeneration, such as in the mallee (Malanson 1984). Smaller scale disturbances that happen more often than those at a larger scale may favour the growth of competitive species over colonising species as newly opened resources are made available (Miller 1982) with the intensity still being the critical factor (Malanson 1984). The competitive species would benefit more from small scale disturbances as long as the intensity is not above a critical level and species diversity would increase according to the model developed by Miller (1982). As fire is one of the main forms of natural disturbance in semi-arid areas such as Pinkawillinie CP, it is one of the main characteristics that has shaped the evolution of the species present (Specht 1979). Therefore, the vegetation is adapted to the removal of above ground parts, but not below ground disturbances. Many of these species require fire as a trigger for germination (Dixon *et al.* 1995).

Since the clearing of land for agriculture leaving only remnants of native vegetation, and the land use by Aborigines has ceased, fire regimes have altered. The frequency and intensity of disturbance determines whether invasion by non native vegetation is likely (Hobbs and Huennecke 1992). Frequent fire can correspond to a decline in native cover, richness and diversity, a shift from native to introduced species, changes in the relative importance of fire response categories, and loss of native resprouting shrub cover (Fisher *et al*. 2009). These changes would also occur with frequent clearing of vegetation by other means as has occurred in the Eyre Peninsula (Australian Government 2009). However, Hester and Hobbs (1992) found that invasion by weeds was restricted to the edge of remnants within a West Australian wheat belt, and found that weeds declined in adjacent woodland after fire. In another instance after a fire in heathland vegetation weed invasion only occurred along the roadsides where grading had previously been conducted, and the soil was disturbed (Hobbs and Huenneke 1992). In mallee vegetation a marked increase can be expected in the number of species following a fire, providing there is adequate rainfall to allow full expression of the potential diversity (Zimmer 1940b). In fire management there is the same problem with the use of tracks to provide firebreaks as there is with the use of tracks for mineral exploration. One of the consequences of fire tracks is that if there is some regeneration of vegetation along them, which is often grasses, there is a potential for fire to move along these tracks at a faster rate than within the main vegetation (WFORG 2007). If fire were to occur in Pinkawillinie CP it maybe a leading influence in the regeneration of vegetation along tracks, particularly as the vegetation requires fire to germinate. However, the intensity would be an important factor and a number of good rainfalls after the event would be necessary. There could also be the increased possibility of weed growth being encouraged if the propagules are present (Hobbs and Huenneke 1992).

b) Human induced disturbance

Human induced disturbance can be caused in several different ways. Two of the increasingly significant forms of disturbance in protected areas are the use of off-road vehicles for tourism (Buckley 2004), and mining and mineral exploration practices (Farrell and Kratzing 1996). These uses produce linear disturbances which affect large areas, as do roads, railroads, powerlines, seismic survey lines and pipelines. These types of anthropogenic disturbances can produce land fragmentation, soil erosion, changes in water dynamics, different competition patterns within the vegetation communities and changes in below ground biota. As large tracts of land in Australia have been cleared for agricultural practices, there has been a substantial amount of literature produced on habitat fragmentation on a large scale and its impact on various biological systems (Curtis 1956, Romney *et al*. 1981, Harris 1984, Hobbs 1993). While the literature includes some studies on linear disturbances in arid environments (Eckert *et al* 1979, Adams *et al* 1982, Dregne 1983, Webb 2002), these mainly relate to recreational activities in the Mojave Desert in the USA, which result in a different pattern of disturbance than that from mineral exploration.

During mineral exploration a grid of access tracks is formed to assess a large area for the presence of the minerals sought. With the creation of smaller patches of undisturbed vegetation separated by linear areas of disturbance at a different successional stage, the species diversity and habitat would possibly be altered (Hobbs and Huenneke 1992). The influence of this fragmentation is somewhat dependent on the width of the linear disturbance and the size of the patches formed. The impact on ecosystem functioning of this type of linear disturbances is poorly understood, particularly in arid and semi-arid systems. Studies to assess the influence of disturbance can be conducted by comparing the characteristics of the ecosystem in the disturbed area with the neighbouring undisturbed area (Skarpe 1990, Carrilo-Garcia *et al* 1999).

c) Introduced plants and animals

Disturbance such as that afforded by the clearance of tracks increases access through natural environments, and so will increase the possibility of the introduction of non native plants into these areas (Hobbs 1989, Rejmanek 1989, Trombulak and Frissell 2000, Myers and Bazely 2003). Weeds and diseases of plants and animals can be introduced into areas by the vehicles using roads for recreational activities (Lonsdale and Lane 1994) and by those used in mineral exploration (Buckley 1986). The introduction of weeds is particularly a possibility when roads and tracks pass through remnants of native vegetation from surrounding agricultural areas, as these areas often have weeds in the roadside vegetation (Milberg and Lamont 1995). There is also a possibility that numbers of feral animals will increase, including predators, such as foxes and cats (May and Norton 1996) and grazers, such as camels (Gauthier-Pilters and Dag 1981). In arid Australia the grazing by feral animals such as camels, pigs, goats and rabbits limits recruitment in many shrub and tree species (Australian Govternment 2009). The composition of the native flora and fauna is affected by the presence of such feral predators and invasive species have become one of the major concerns for the conservation and management of natural ecosystems (Hobbs and Huenneke 1992).

d) Factors affecting ecosystems

The initial effects of disturbance are short-term, for example, there may be temporary loss of plant cover, resulting in changes to the microclimate, amount of woody debris, topography and soil dynamics. Effects consist of the direct damage to the existing plants, while the longer-term effects could include the complete extirpation of species limited by their dispersal methods. There can be subsequent effects over a longer term still, to the successional development of the vegetation and the subsequent changes in species composition. These changes over time relate to the stability and organisation of the community (Connell and Slatyer 1977). The first species to colonise a newly cleared site are often the fast growing, well dispersed ruderal species, which then change the environment to favour subsequent species. This has been described as a facilitation model (Connell and Slatyer 1977). Alternatively, any species that can colonise the area straightaway can either follow a tolerance model or, an inhibition model, which involves the inhibition of subsequent colonists (Connell and Slatyer 1977). The type of succession is reliant on whether the environment caused by the clearance of vegetation and subsequent use of the tracks needs to be changed by early successional species to enable colonisation by later successional species, or whether later species can colonise directly. The species following the tolerance model could survive changed conditions better than those characterised as early successional or those that are inhibited by these conditions. The type of successional process that occurs is reliant on the way the later species become established once propagules arrive. For example, if soil compaction is the main result of a disturbance, for the facilitation model to be the mechanism of succession, plants that break up the soil would grow. This would mitigate this consequence of the disturbance and enable the growth of later plants, which were originally restricted from becoming established by the compacted soil. So, for example, annual species and grasses would not have the effect of breaking up compacted soil as their root systems are very shallow (Leishman and Westoby 1992), and so would not influence growth in this aspect. The growth of later successional perennial plants in a disturbed area would indicate the tolerance mechanism to be in place, as these are able to grow with greater root compaction. If a thick growth of annuals and grasses occurred in the disturbed area, this could inhibit the successful establishment and growth to maturity of later successional perennials. This would indicate that the mechanisms described in the inhibition model would be at play. Evidence of this is provided in studies conducted by McCormick (1968) and Armesto and Pickett (1986) where pioneering annuals were removed and the perennial plants grew faster and flowered earlier. In the facilitation model the early successional plants would possibly be less resilient to any further disturbance, even though they have been shown to recover more quickly (Sousa 1980). The most likely models of secondary succession would probably be the tolerance and inhibition models and not the facilitation model, as the latter would most likely be the case in primary succession (Connell and Slatyer 1977). To envisage the quickest recovery of a disturbed system it is important to assess the community composition that is the favourable result, and to determine the likely succession process in terms of the aforementioned three models (Connell and Slatyer 1977).

In general, the role of competition in the vegetation structure of an ecosystem is apparent in the initial recruitment of plants from seed. As Harper (1977) pointed out, the earlier that individuals emerge, the more opportunity there is to utilise space and the resources associated with that space from their neighbours. It is difficult to know the reasons for competitive success, however resource partitioning can be demonstrated in the way species in the same community utilize resources (Schoener 1974). Studies of this resource partitioning can be used to assess the interspecific competition that allows several species to live in a stable coexistence (Schoener 1974). There is also the ability of some initial colonising species affecting the environment by producing chemicals that leach into the soil, and so inhibiting germination of other species (Laterra and Bazzello 1999). We know little about succession in arid and semi-arid systems making it very difficult to predict the consequences of newly introduced disturbances to these systems. As drought and salinity are the most important abiotic factors limiting plant growth and yield in many areas (Zhang *et al*. 2006), the competitively superior species are often those that can withstand these stresses the most successfully.

Soil formation in semi-arid areas is slow and easily disrupted and its ability to recover is limited (Dregne 1983) as biological activity is generally low. The episodic heavy rainfall events necessary for the growth of vegetation is the main factor influencing soil formation (Dregne 1983). In mallee ecosystems, Preece (1989) is of the view that, it is vital that to ensure their conservation the continued clearance of these areas should be prevented, and the incremental degradation of their quality also guarded against. It is a fragile environment due to this lack of resilience to disturbance, and so can be degraded easily.

The method of formation of the mineral exploration tracks along with their placement in the landscape and timing of clearance will affect the properties of the disturbance. The number of passes along the tracks and the type of vehicles used are significant. Even with just one pass annual and perennial plants, desert pavement, microflora and mechanical crusts may be disrupted. To assess the duration of impact the results from quantitative studies can be extrapolated to predict continuing trends. This would involve the more indirect processes of erosion, sedimentation and changes of surface runoff patterns (Wilshire 1983). With these indirect physical processes are the changes in nutrient status of the environment (Ludwig *et al*. 2005). The movement of nutrients and litter can result in accumulation of nutrients in some areas and removal from others (Ludwig *et al*. 2005). Along with this there will be the differences in litter deposition on the soil surface, and the consequent heterogeneous shading and temperature. The type of soil present where tracks are cleared gives an indication of the possible extent of the impact on the ecosystem. The clay and sand content are important factors in determining the water infiltration and runoff and the extent to which soils are susceptible to compaction. The surface characteristics and topographic position are also relevant in determining the amount of erosion that is likely to occur. Wind erosion will occur when the soil surface is exposed and dry and powdery along the tracks. The introduction of feral animals such as goats and camels can result in an increase in soil compaction and erosion.

To define the potential threat to the environment of off-road vehicles, a quantitative assessment of the impacts is necessary along with an initial understanding of the variability and functioning of the environment (Kockelman 1983). For example, Webb (1983) pointed out that a quantitative prediction of soil compaction (and related water infiltration) is of fundamental importance in the management of the fragile ecosystems in arid and semi-arid environments.

It is important to determine which of all these factors have the most influence on the vegetation structure. For monitoring purposes these factors could then be concentrated on in future assessments. The introduction of weeds is a distinct possibility as they could be brought in from surrounding agricultural areas on vehicles and by feral animals. A major disturbance occurring over that already caused by the presence of the tracks, for example, intense fire or drought could magnify the effects that have already been caused.

This thesis provides new insights into the important variables involved in linear disturbance to the environment and uses quantitative studies of these factors to provide an information resource for industry and further research. This study was conducted in the semi arid environment of Pinkawillinie Conservation Park in South Australia, which is characterised by mallee vegetation. This area has significant conservation value and is also of considerable interest to the mining community.

The overall aims of this thesis are to answer the questions:

- Are the physical and chemical characters of the ecosystem affected by the linear disturbance created from clearing and using tracks for mineral exploration, and if they are, how are they changed?

- How do these changes affect the dynamics of vegetation growth?
- What are the implications of these ecosystem changes on the functioning of the system?
- How can the information gained from the above be extrapolated to the future ecosystem productivity and what are the possible features to be addressed in future regeneration attempts?

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Chapter 2 Description of the system

2.1 General description

Pinkawillinie Conservation Park (Figure 2.1) lies between coordinates 135^0 28.5' E and 136^0 15' E and 32^0 45'S and $33^0$12'S, in South Australia. It consists of a corridor of mallee dune country slanting from northwest to southeast in north-central Eyre Peninsula in South Australia. The name 'Pinkawillinie' is of Aboriginal origin and the most widely accepted translation is, 'place of many rabbit-footed bandicoot burrows' (DEH 2002b). The park's northern boundary is the southern boundary of Gawler National Park and the east, west and south are surrounded by agricultural land.

On Eyre Peninsula 43% of the land is covered in native vegetation, and of this 4%, approximately 219,000 ha, is within Conservation Parks, (DEH 2002a). More than half of this comprises Pinkawillinie CP with 130,813.48 ha (DEH 2002a). The park was declared in 1970 (Australian Government 1999).

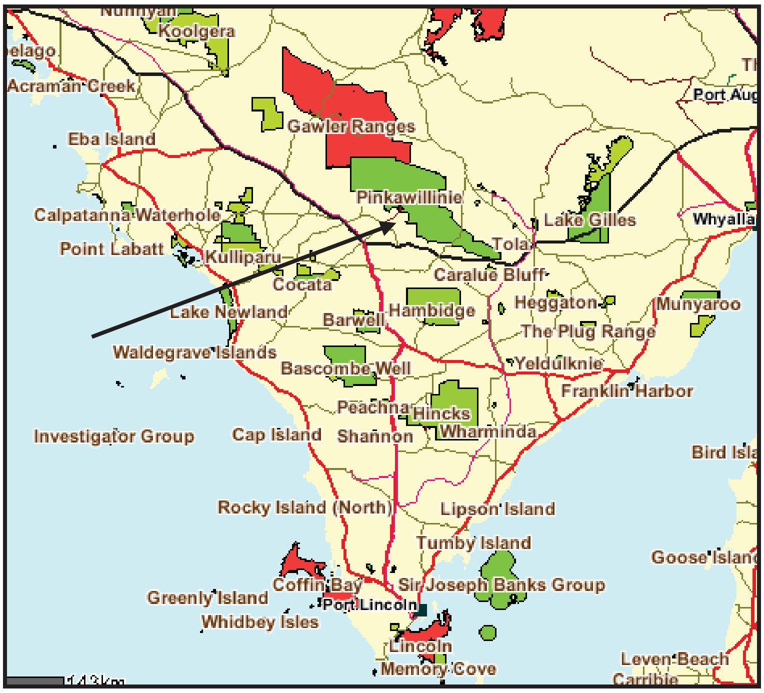

Figure 2.1 Position of Pinkawillinie Conservation Park on Eyre Peninsula

2.2 Geology and Soil

Eyre Peninsula is part of the Gawler Craton, a complex of metamorphic and igneous rocks of Precambrian age (Wasson 1982). This region has long remained stable with little evidence of marine incursions in the Cainozoic, but calcrete is common and occurs in a thin layer, with surficial sheet calcrete being a prominent feature of western Eyre Peninsula (Blackburn and Wright 1989). The sand dune system in which Pinkawillinie CP is situated is part of the larger Eyre Dunefield (Wasson 1989). The area is known in geological terms as the Corrobinnie Depression. This is an elongated depression, thickly mantled with sand, forming numerous parabolic dunes, with isolated hills of volcanic or metamorphic rocks (Prineas *et al*. 1986).

Pinkawillinie CP is an example of a semi-arid area, with typically shallow and/or nutrient deficient soils (Hill 1989), where there has been no cropping due to the extremely low nutrient status of the soil. Solonised brown soil is prominent in this area and varies from dark grey to red-brown at the surface to almost white at depth (Blackburn and Wright 1989). The red-brown earths of the Corrobinnie Depression are characteristically an ironstone gravelly version (Wright *et al*. 1989). The texture can vary from sandy to clayey, and along with an increase in clay content, alkalinity can be between pH 8 and pH 9 with subsoils often more alkaline than this (Prescott and Piper 1930, Blackburn and Wright 1989). Siliceous sands, which are also part of the soil profile of Pinkawillinie CP, have been classed as podzols. Water repellence can occur with these soils due to exudates from fungal hyphae (Blackburn and Wright 1989).

2.3 Climate

The park lies in a semi-arid region between the 250 mm and 450 mm isohyets, north of the Goyder’s line, i.e. the line above which it is considered climatically not suitable for arable farming (Sparrow 1989b). There is no surface water making it unsuitable for grazing. The seasonal pattern is Mediterranean-type, with cold, wet winters and hot, dry summers. However, there are decadal fluctuations in rainfall, which are largely due to fluctuations in large summer rainfall events (McInnes *et al* 2003). In the period of this study the rainfall in Wudinna (the closest weather station to the study site) in March in 2007 was the highest in one month than in any other month over the three years, with the rain falling on only three days. This high rainfall event was after a period in February of no rain (Figure 2.2).

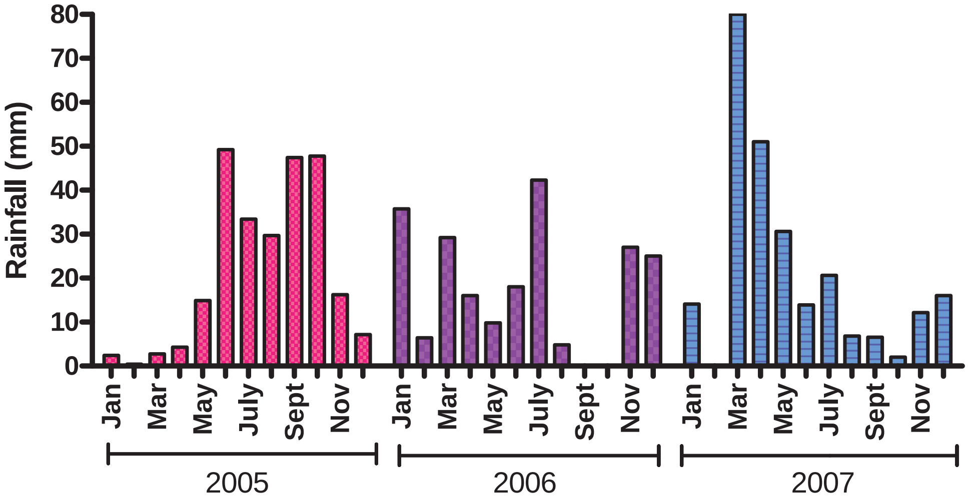

Figure 2.2 Rainfall record for the period of the study (2005, 2006 and 2007) from Wudinna (Figure 2.5) – the closest weather station

The rainfall pattern in 2005, the first year of the duration of this study, was similar to the mean of the past 79 years in Kyancutta, with most falling in the winter months (Figure 2.3). In 2006 there was some winter rainfall with more summer rainfall than in 2005, and in 2007 most rain fell in the summer months (Figure 2.2).

NOTE:
This figure is included on page 13
of the print copy of the thesis held in
the University of Adelaide Library.

Figure 2.3 Mean rainfall records for the past 79 years in Kyancutta (Figure 2.5) – a weather station to the south of the park

The mean maximum temperature has been highest in the summer months with 33^0C in January and lowest in the winter months with 4^0C (Figure 2.4).

NOTE:
This figure is included on page 14
of the print copy of the thesis held in
the University of Adelaide Library.

Figure 2.4 Mean temperature records for the past 79 years in Kyancutta (Figure 2.5) – a weather station to the south of the park

There have been no recorded fires in the area of this study since 1931, when records started (DEH 2009).

2.4 Vegetation of Pinkawillinie CP

Pinkawillinie CP is situated in the Interim Biogeographic Region for Australia (IBRA) Eyre Mallee IBRA Subregion (EYB5) and contains 70% of the total floristically mapped vegetation on Eyre Peninsula, made up of 45 mallee plant communities (DEH 2002a). Conservation parks are areas under the National Parks and Wildlife Act 1972 that are protected for the purpose of conserving wildlife or the natural or historic features of the land, where the development of visitor facilities tends to be kept to a minimum (South Australian Government 1972).

The term “mallee” was used by Aborigines to describe the water mallee which was usually a large mallee tree whose shallow roots provided much needed water for drinking

(Noble and Bradstock 1989). The mallee habit, that of multiple stems arising from a large lignotuber, has evolved in eucalypts to cope with low nutrient soils and low rainfall. Eucalypts are also adapted to withstand fire (Mullette 1978, Beard 1989). According to Sparrow (1989b) the major environmental factor in determining areas covered by mallee vegetation is low soil moisture. The flora of Eyre Peninsula has representatives of species at the eastern limit of those centred in Western Australia and the western limit of eastern distributions (Sparrow 1989b). The ancestors of most of the mallee eucalypts originated in south-western Western Australia and then extended into the centre and east during later climatic fluctuations, and so the species of the mallee region are relative newcomers to the east (Hill 1989).

The vegetation in the area of this study is characterised by an upper strata of mallee eucalypts, mainly *Eucalyptus incrassata*, and *Callitris verrucosa*, while the mid layer is dominated by *Melaleuca uncinata* (broombush) and the ground layer features *Triodia* spp. The eucalypts here are adapted to fire and have epicormic buds and underground lignotubers. *M. uncinata* also can re-sprout from lignotubers. *C. verrucosa* is an obligate reseeder and requires fire to open their cones to release the seeds for germination. *Triodia* can spread by rhizomes or by the release of seeds. A number of annual species including *Calandrinia* spp. and *Crassula* spp. germinate in winter. The soil surface is characterised by a covering of a biological crust which consists of a complex mix of cyanobacteria, lichens, algae, liverworts, fungi, bacteria and mosses (West 1990).

2.5 The value of mineral exploration in the area and its ecological impact

The Gawler Craton, in particular, the Central Gawler Gold Province, within which Pinkawillinie CP is situated, contains mineral resources of gold, copper and silver. Mineral exploration companies and governments are becoming increasingly aware that it is important to understand ecological processes, which should lead on to forming environmental guidelines. These guidelines, if implemented, could possibly prevent or at least minimise the degradation of the environment. This is a change, as in the past the negative impacts of mineral exploration were not considered (Dobrzinski 1998). There have been a number of companies exploring in Pinkawillinie CP since 1971 conducting different amounts of clearance and drilling (Appendix 2).

The method of clearance of tracks and their positioning

Mineral exploration involves clearing tracks to give access to drilling sites. Two aspects to the initial clearing of tracks are the method of clearance and the positioning of the tracks. Both aspects have a large influence on any adverse impacts to the environment. The two methods of track clearance in this region have been: bulldozer with the blade down to scrape off the whole top layer of soil and vegetation, and a bulldozer with the blade raised and a concrete roller towed behind to flatten the vegetation. The first method was used to clear a set of tracks in the late 1980's just outside the boundary of Pinkawillinie CP (Dobrzinski 1998). It was noted that 11 years after clearing there was very poor regeneration as the mallee lignotubers had not sprouted (Dobrzinski 1998), and it would be expected that the seedbank would have also been destroyed. There was also the formation of large windrows along the edges, large piles of dead vegetation and piles of very hard Kaolinite drill cuttings (Dobrzinski 1998). The second method of flattening the vegetation has had less observable impact. Tracks formed in 1992 and reassessed in 1998 were found to have rootstock revegetation almost covering the tracks and some ephemerals and annuals germinating (Dobrzinski 1998). This latter method of clearing tracks was used in all of the subsequent mineral exploration by Adelaide Resources Limited in Pinkawillinie CP.

Clearing was carried out using a GPS making it unnecessary to use the line of sight method, and so reducing the need for straight lines. Adelaide Resources Limited rolled out the tracks within the swales as much as possible to reduce the visual impact caused by tracks going up and over sand dunes (Drown *pers comm*. 2005). To minimise the recognition of the tracks by the general public and deter use by four-wheel drive enthusiasts an effort was made to place the tracks at an acute angle to the main track. In the exploration process drill holes were placed at approximately 50 – 200 m intervals and all the soil from the drill holes were taken out of the park. Trees were also taken into account when the access tracks were cleared.

Study Site

Pinkawillinie CP has a number of tenements, i.e. a claim, lease or licence under the Mining Act 1971 (South Australia Government 1971), which consist of tracks cleared of vegetation to enable mineral exploration for gold and copper to take place. These provide access for drilling to assess the viability of mining these resources. There are more tracks in some tenements than others and more drill holes in some than others. This study was conducted in the tenement known as Baggy Green (WUD6) (Figure 2.5, Appendix 1).

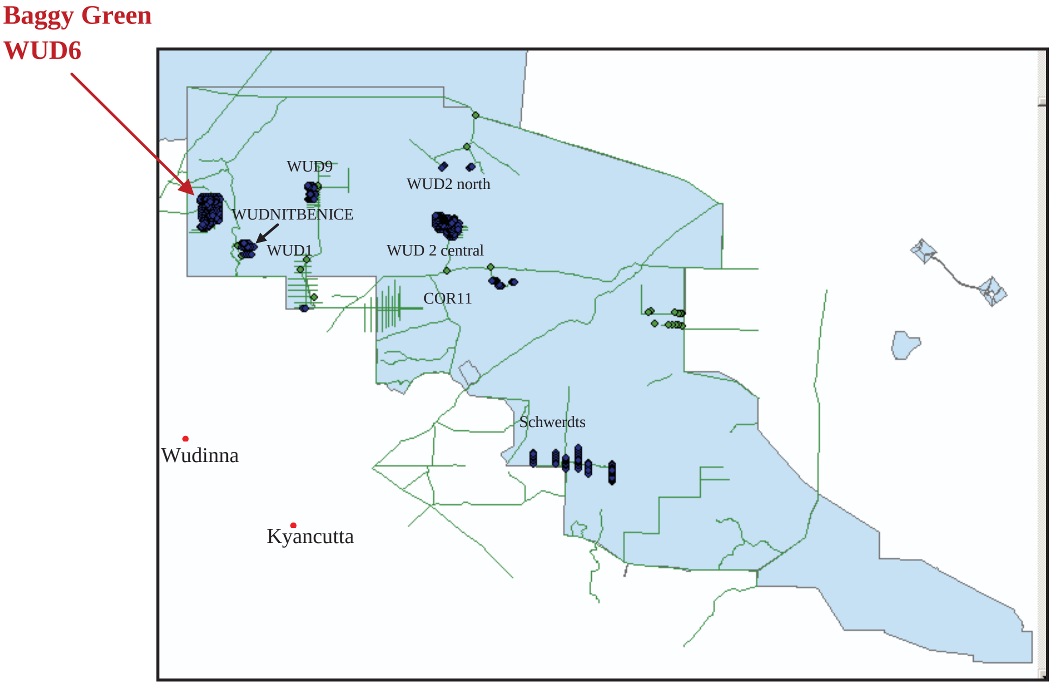

Figure 2.5 Pinkawillinie CP – showing Baggy Green (WUD 6) and other tenements

Of the 17 horizontal tracks cleared for exploration in the Baggy Green (WUD) tenement sections of three tracks were studied in detail for the impacts of disturbance (Figure 2.6, Appendix 2). The choice of tracks for this study was limited to those where drilling for exploration had ceased, at least for the duration of this study. The three tracks chosen appeared similar in soil, vegetation and degree of impact, and were equivalent for ease of access to a suitable section of slope so as to minimise impacts by vehicles used in this study (Figures 2.7, 2.8 and 2.9).

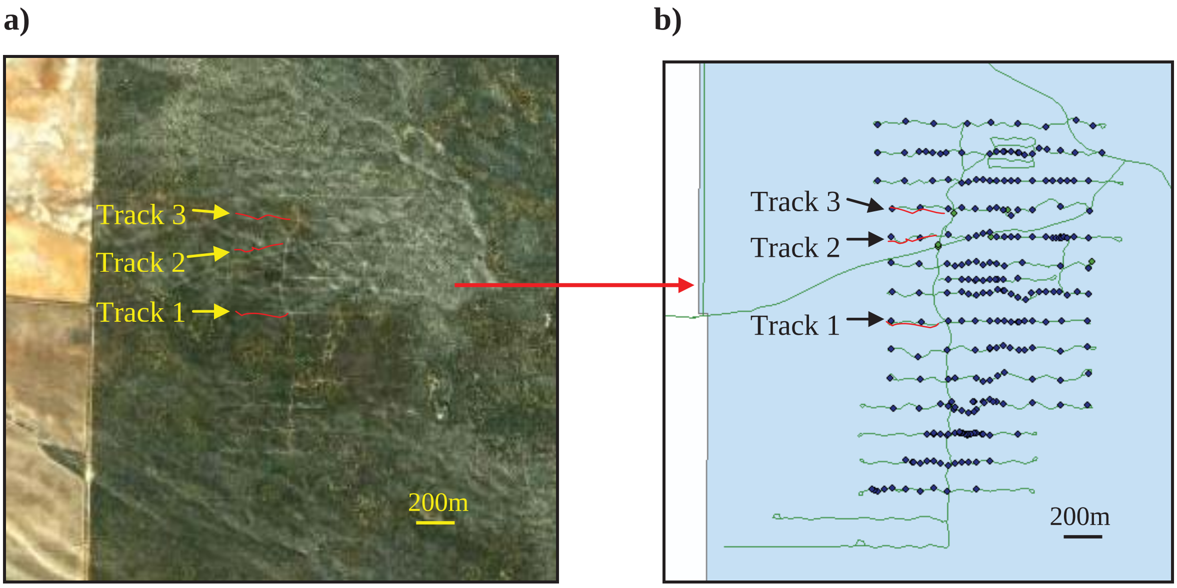

Figure 2.6 Baggy Green (WUD6) – a) aerial photograph, b) map showing tracks and drill sites – highlighting the three tracks chosen for this study

Figure 2.7 Track 1 – looking down to the swale

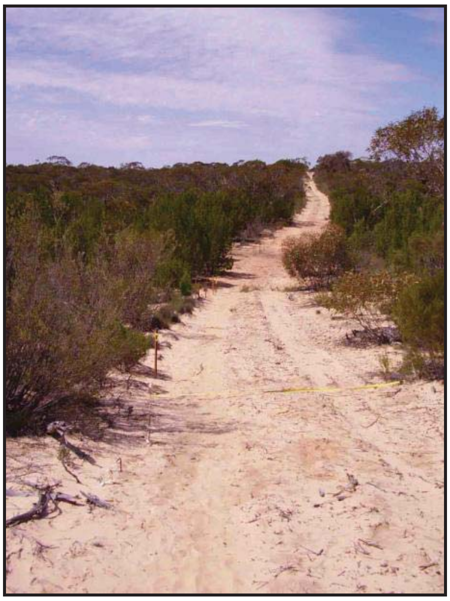

Figure 2.8 Track 2 – looking down to the swale

Figure 2.9 Track 3 – looking down to the swale

Track 1 – 92 metres long, west facing, altitude 430 ft to 442 ft, 12ft – 2.28^0 slope
Track 2 – 61 metres long, west facing, altitude 401 ft to 459, 58 ft – 16.85^0 slope
Track 3 – 63 metres long, south east facing, altitude 365 ft to 389 ft, 25ft – 6.95^0 slope

The length of tracks in Baggy Green was 33.2 km resulting in approximately 0.34% of the area of the Baggy Green tenement being cleared. Tracks 1 and 2 were cleared in 1999 four years before Track 3 (Table 2.1). Usage of the tracks varied (Table 2.1), but they all had vehicles over them in 2004, and so the last time of "impact" was the same for the three tracks.

Table 2.1 Times when tracks were cleared and AC shallow air core drilling, RC deeper reverse cycle drilling conducted

Track 1					
	1999 summer	**1999 winter**	**2003 spring**	**2004 summer**	**2004 winter**
AC	5	2	3	0	0
RC	0	0	2	3	2
Track 2					
	1999 summer	**1999 winter**	**1999 winter/spring**	**2003 spring**	**2004 summer**
AC	5	4	4	1	4
RC	0	0	1	3	1
Track 3					
				2003 spring	**2004 summer**
AC				7	4
RC				1	1

During exploration, tracks were created by a concrete roller towed behind a tractor. They were traversed twice by a drill rig (one return trip) and a number of times by support 4WD vehicles (Drown 2003). The vehicles used were: the initial tractor towing the concrete roller, a vehicle for Rotary Air Blast (RAB)/Aircore (AC) drilling, a heavier vehicle for Reverse Circulation (RC) drilling and support 4WD vehicles for the transport of fuel, drill rods and personnel during operations (Price 2004). The soil from the holes was collected and removed from the site involving a number of passes by 4WD vehicles. Diamond core drilling was the next step in the exploration process and this involved a truck mounted drill similar in size to a mobile RC drill, an accompanying truck for equipment and a water truck.

Data was collected from four sections along each track and from four sections across the track (Figure 2.10).

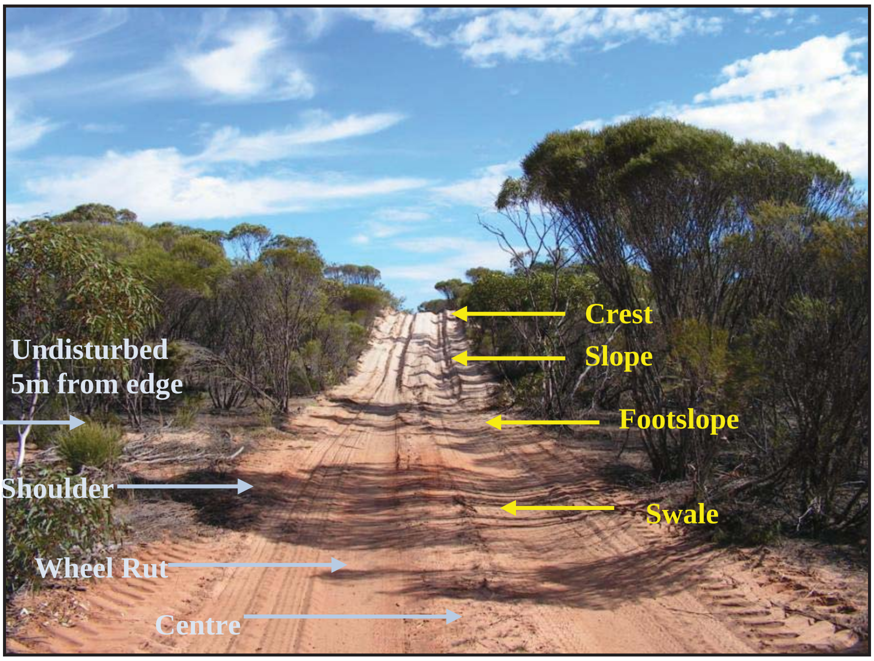

Figure 2.10 Track in Pinkawillinie CP showing the positions from which data was taken (This track was not used in this study.)

2.6 Conservation status of the study area

Pinkawillinie CP is part of the South Australian Government's NatureLinks Program**,** which attempts to connect core protected areas for the preservation of habitats (DEH 2004). Pinkawillinie CP has been rated by the International Union for Conservation of Nature (IUCN) as Category 1A – Strict Nature Reserve (DEWHA 2004). It is, therefore, an area which is set aside to protect biodiversity and also geological/geomorphological features (IUCN 2009). To ensure this, the number of people visiting the area should be limited and any use and subsequent impacts should be strictly controlled to ensure protection of the conservation values. Such protected areas can serve as indispensable reference areas for scientific research and monitoring (IUCN 2009). The area is under a current native title claim (Barngarla 2006). The company exploring for minerals at Baggy Green tenement planned all exploration activities such that sacred sites were avoided. These were located by a survey team including the Wirangu, Biringa, Barngarla and Nauo groups who have lodged native title claims covering the area in 1998.

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Chapter 3 Effects of disturbance on the landscape and ecosystem processes - Physical characters

Introduction

As the tracks in this study are all perpendicular to the dune crests, the clearance of vegetation and changes to the soil characteristics caused by the use of off road vehicles are likely to change ecosystem transport processes (Brooks and Lair 2005). These changes can affect spatial distribution of resources and consequently the species composition and the productivity of the ecosystem could be changed.

Compaction and Bulk Density

The passage of vehicles disrupts the surface soil through a shear effect and through compaction (Harrison 1976, Eckert *et al*. 1979, Dregne 1983). The microbial crust, which stabilises the soil, is destroyed, increasing the potential for erosion (Belnap and Gillette 1998) (Figure 3.1) Increased compaction can result in decreased pore space (Lull 1959), a corresponding increase in the bulk density of the soil and a reduction in water infiltration rates (Edgar 1978) (Figure 3.1). Soil compaction results in an increase in density and strength of the soil (Webb 1983), the latter being the maximum resistance of a soil to shearing stresses. Compaction can contribute to accelerated erosion (Snyder *et al*. 1976) and decreased plant growth (Grimes *et al*. 1975, Webb 1983) (Figure 3.1). The mechanical resistance of soil to expanding roots is best characterised by penetrometer soil strength measurements (Taylor 1971, 1974). Any decrease in plant growth arising from this reduced root exploration is due to less pore space in the soil and less available water. There is also less gas exchange, and so problems associated with reduced aeration are likely to occur. This results in decreased absorption by roots of major mineral nutrients (Kozlowski 1999). The growth of mycorrhizal fungi has also been found to be compromised by compaction, which could also minimise the availability of nutrients for plant growth (Entry *et al*. 1996).

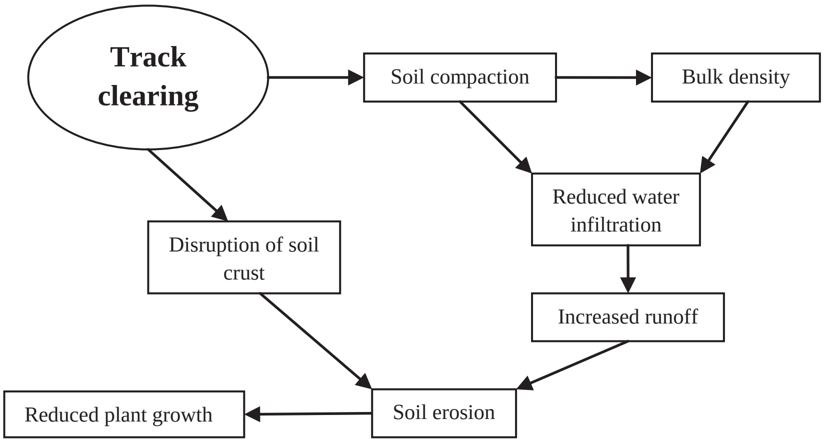

Figure 3.1 Diagram showing a general model of the interaction between different landscape units (Hinckley *et al*. 1983, Webb 1983)

The susceptibility to compaction of different soil types varies considerably (Webb *et al*. 1978). Soils of loamy sand are most susceptible to density increases under loading (Bodman and Constantin 1965, Webb 1983, Lovich and Bainbridge 1999). Therefore, the chance of compaction occurring with vehicle usage is highly likely. Vehicles traversing tracks can increase soil density to a depth of one metre (Snyder *et al*. 1976), however the increase is usually just below the surface in the top 30 cm (Kozlowski 1999). The amount and nature of the destruction of annual vegetation and compaction of soil depends on the number of passes of a vehicle (Webb 1983). Density near the soil surface increases logarithmically as the number of vehicle passes increases, indicating that the greatest changes in soil properties occur during the first few passes (Webb 1983, Kozlowski 1999). This change per pass decreases as the inverse of the number of passes (Webb 1982). While there have been some studies on soil compaction and water infiltration in agricultural systems, there have been very few studies conducted on this type of disturbance in natural environments, except in the Mojave Desert (Webb 1983), and none have been conducted in dunal systems such as Pinkawillinie CP. There is, therefore, very little information on the long-term impacts.

Water Infiltration

With the vegetation clearance from linear disturbance, and the resultant compaction, the water infiltration and run off patterns are likely to be significantly changed (Brooks and

Lair 2005). Clearing removes deep-rooted plants, and so water flows into the soil are through piston flow, i.e. uniform movement of water through soil. The surface water percolating through the soil with piston flow can result in the water table rising and hence an increase in salinity (Cook *et al*. 1989). Bypass flows make use of the spatial heterogeneity within the soil through cracks and fissures, such as root channels, and are less likely to raise the water table. Compaction can cause a significant decrease in infiltration rates and be the most important factor leading to increased erosion when the water runs off (Webb 1983). Edgar (1978) also found that the water regime affected by compaction was most severe on tracks in the Mojave Desert that were used repeatedly.

Water Dynamics and Soil Erosion

The initiator of sediment movement down a slope is often raindrop impact from high intensity storms. These weather events can occur periodically in summer in the arid and semi-arid zone of Australia, mainly north of 30^0 latitude, due to the southward penetration by humid tropical air masses (Simmers 2003). There has been little research conducted on the water dynamics and erosion potential in mallee areas of the semi-arid zone below this latitude, where this weather pattern can also occur. The amount of sediment movement is reliant on the soil surface and the ease by which particles are dislocated (Hinckley *et al*. 1983). The surface crusts can inhibit this dislodgement by raindrop impact. However, if the rainfall event is strong enough it may cause the disruption of the integrity of the soil crust resulting in the dispersal of the nitrogen fixing cyanobacteria and lichens within the sediment (Barger *et al*. 2006). Vehicular traffic destabilise the crust on the soil surface, and so the soil particles are more likely to be detached by water or wind movement, resulting in an inevitable increase in the rate of erosion (Hinckley *et al*. 1983). Any redistribution of these low nutrient soils in such a fragile ecosystem is likely to exacerbate the damage due to the original disturbance of clearance and compaction.

Since compaction reduces the infiltration capacity of the soil, water runoff can increase in frequency and intensity (Hinckley *et al*. 1983). Iverson (1980) showed that overland flow sediment transport capacity was proportional to flow power (rate of water movement) raised to an exponent of about 1.5. Where tracks are cleared straight down a slope, vehicles using tracks create smoother trails than in the undisturbed area, and so the runoff follows a straighter flow path and therefore is more readily channelled (Hinckley *et al*.

1983). If this channelling occurs the rate of erosion is greatly accelerated (Kirkby and Kirkby 1974). This is a possible outcome where tracks have been cleared in Pinkawillinie CP. If erosion occurs due to water periodically collecting and running along the tracks, the cumulative effects of off-road vehicle impacts may not be known for years or even decades after the original disturbance (Vollmer *et al*. 1976).

It is of vital importance to examine the initial disturbance and therefore provide information on the possible nature and likelihood of subsequent impacts so as to minimise them. In the study site the topographical features of the landscape and soil characteristics are likely to be a major influence on the transport processes of the area. There is a large gap in the knowledge associated with these processes in this type of environment.

The aim of this chapter is to answer the following questions:

- Were the physical characteristics of soil compaction and bulk density greater in the disturbed areas than in the undisturbed areas within mineral exploration areas of Pinkawillinie CP?
- Did these characters differ with respect to the topographical features and soil structure of the study site?
- How were the patterns of infiltration changed?
- Was there more soil movement down the tracks than in the undisturbed area?

Methods

The data sets were collected from three tracks at four positions across the tracks (microtopography) and four positions along the tracks (topography) (Figure 3.2). Details of the location of tracks and how they were created are given in Chapter 2.

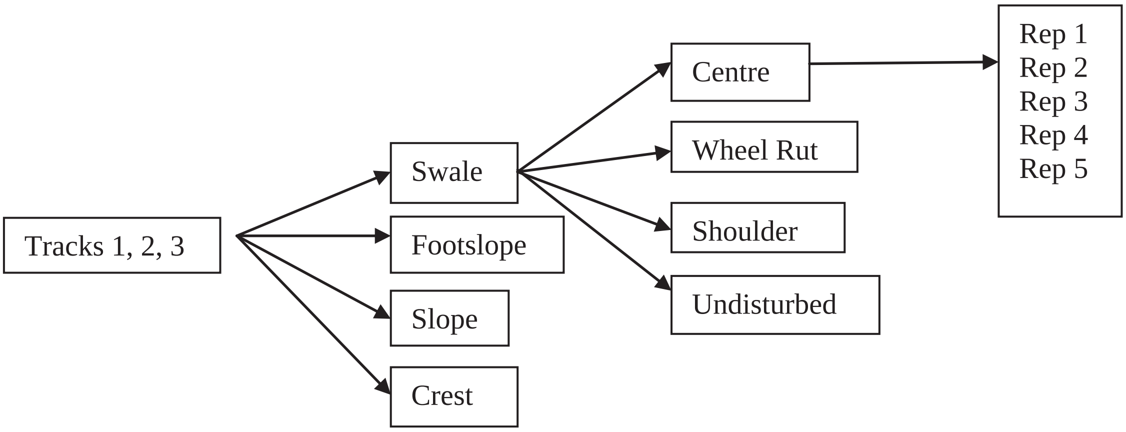

Figure 3.2 The positions from which data sets and samples were obtained – some analyses only used the swale, slope and crest; some used five replicates and some the three tracks were used as replicates

3.1 Soil colour and Texture

An objective measure of soil colour: with hue (shade) e.g. YR; value (lightness); and chroma (intensity), was obtained by comparison of soil samples from each position across and along the tracks with Munsell color charts and this resulted in 48 scores.

To determine the texture of the same soil samples the soil was placed in the palm of the hand, moistened and worked up with the fingers of the other hand to eliminate structure. A ribbon was then formed by pushing the soil out between thumb and forefinger and the length of this ribbon determined the texture class (Northcote 1979).

3.2 Compaction

A Bush Recording Soil Penetrometer (manufactured by Findlay, Irvine Ltd, Scotland) was used to measure soil compaction by recording resistance at 3 cm intervals to a maximum depth of 45 cm (to an accuracy of +/- 1 mm). This device consisted of a rod with a solid cone of 12.9 mm diameter which was pushed into the soil until a high pitched sound indicated that the cone couldn’t be pushed through any further without damaging the equipment. Force was measured by a strain gauged transducer, accurate to better than 1% over the range 0-50 kg. Twenty sets of readings (4 x 5) in kgf from a digital readout were obtained at each section along the tracks. These were at the swale, footslope, slope and crest at five randomly appointed points assigned (from a random number generating program) within a measured five metre section, at the centre, wheel rut, shoulder and five metres from the shoulder in the undisturbed area (see Figure 2.10). This resulted in 240 readings for the three tracks. This work was done in September (spring) in 2005. Statistical analysis was conducted using the compaction readings for four depth categories: 0-3 cm (surface roots), 6-15 cm (shallow roots), 18-24 cm (0.5 roots), and 27-45 cm (deep roots) inclusive**.** The data was averaged for the readings within each category e.g. readings at 6 cm, 9 cm, 12 cm and 15 cm were totalled and divided by 4.

3.3 Bulk density

Bulk density was measured by obtaining one intact soil sample from each of the positions across and along the three tracks using a steel cylinder with a 5 cm diameter and 5 cm depth. This was pushed into the top soil down to a depth of 10 cm, resulting in 48 samples which were dried and weighed in the laboratory. The bulk density was measured in micrograms dry weight per cubic centimetre using the volume of the cylinder (98.21 cm^3).

3.4 Soil water content

3.4.1 Soil samples

The soil water content was measured as a percentage of soil weight at different depths using soil samples collected in spring 2005 from depths of 0 cm, 10 cm, 20 cm, 30 cm and 40 cm one from each of the positions across and along the tracks. The 240 samples collected were weighed and then dried at room temperature over a few months, weighed again and the water content determined. As there was a possibility of water being reabsorbed from the atmosphere sometime between the initial drying and subsequent weighing, 35 samples were placed in an oven at 70^0F for four weeks to assess any differences. It was found that there were no significant differences using a Mann-Whitney test between the two readings and so the first scores were used in the analysis (Figure 3.3).

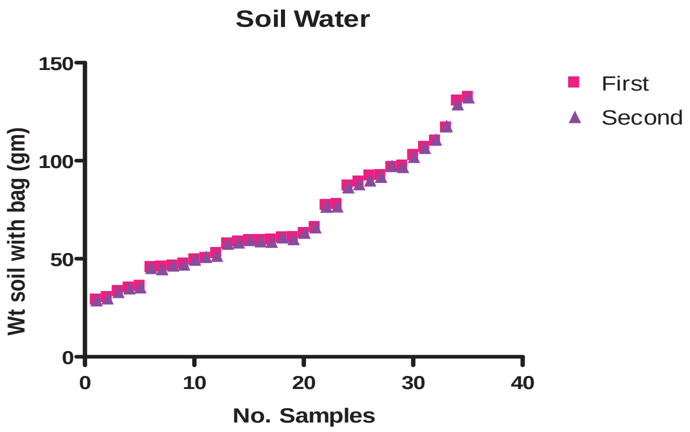

Figure 3.3 Comparison of first and second dry weights of soil samples used for measuring soil water content

3.4.2 Moisture readers

The soil water content was also measured by volume and the time taken for the soil to dry out in the disturbed and undisturbed areas after rain. ECH$_2$O EC-10 probes and Em50 data loggers manufactured by Decagon Devices Inc. were used. The probes measure the dielectric constant of the soil in order to find its volumetric water content. They do this by finding the rate of change of voltage applied to the sensor once it is buried in the soil. Three data loggers each accommodating five probes were placed on each of Tracks 1 and 3 at the swale, slope and crest. The probes were placed vertically into the top 10 cm of the soil with one at each of the positions of centre, wheel rut, shoulder and two in the undisturbed area five metres from the track edge, one under a tree and one out in the open i.e. in a total of 30 positions. The loggers were programmed to take a reading every four hours. They were placed out in the field for 24 weeks in the spring and summer of 2006 and the data periodically downloaded. Technical problems with the probes and data loggers, mainly caused by animal disturbance, resulted in a large amount of missing data. Therefore, only data sets from the swale of Track 1 and the swale, slope and crest of Track 3 have been included (Table 3.1). The data set was from one rainfall event of 23.8 mm on the 12/11/06 beginning from 12 midnight 24 hours before this event to show the differences before and after rain. The data was taken at four hourly intervals for the time period of 0 hours, which was 4am on 11/11/06 to 236 hours at 12 midnight on 20/11/06, when the water content of the soil was back to the same levels as before the rain. This resulted in 60 readings.

Table 3.1 Positions from which data was obtained from moisture readers and used in the analysis for soil water

	Topographic Position	**Positions across the tracks**				
Track 1	Swale		Wheel Rut	Shoulder	UndisturbedOpen	
Track 3	Swale	Centre	Wheel Rut	Shoulder	UndisturbedOpen	UndisturbedUnderTree
Track 3	Slope	Centre		Shoulder	UndisturbedOpen	UndisturbedUnderTree
Track 3	Crest	Centre	Wheel Rut			UndisturbedUnderTree

The standard calibration to calculate the volumetric water content of the soil for the EC-10 probes was $y = 0.000936x - 0.376$ (ECH_2O Dielectric Aquameter User's Manual Version 1.4).

3.5 Soil erosion

Erosion was measured opportunistically due to soil being deposited in trays, which had been set up to assess seed rain. Measurements of the weight of soil accumulated in the trays provided an assessment of material transport. The trays were aluminium foil containers (rectangular in shape - 197 x 105 x 49 mm) with holes in the bottom to let water drain. These were placed on the soil surface. A square wire cage with 1 cm^2 holes and about 8 cm high was placed over the top to prevent small animals from accessing the trays. Trays were placed at each of the swale, slope and crest and on each of the tracks. Four of these trays were placed on the tracks in the wheel rut and four 5 metres from the edge of the tracks in the undisturbed area. These were left in the field over the three summer months and the beginning of autumn 2006/7. During this time there were some intense rainfall events. The aluminium foil containers with soil in were retrieved and weighed and the container weight subtracted to assess differences in soil accumulation between positions. The erosion events represented in this study most likely resulted from the movement of soil during two rainfall events: 22/12/06 - 20.4 mm and 19/1/07 - 15.8 mm.

Statistical Analyses

<u>Compaction</u>

The software package JMPIN 4 (Copyright © 2010 SAS Institute Inc.) was used to test for normality and homogeneity of variances. The Shapiro-Wilks test (D'Agostino and Stephens 1986)_was used to test for normality, with $p<0.05$ indicating non normal data. Levene test (Levene 1960), which is an inferential statistic was used to assess the homogeneity of variances in different samples with $p>0.05$ indicating homogeneity. The compaction data sets were not normal and the variances for positions across and along the tracks, and for depths were heterogeneous, and the track data variance was homogeneous. Transforming the data sets could not rectify this. A multivariate analysis of variance of the compaction measured in kilograms force (kgf) was used to assess the differences in compaction measured between depths when they were nested within positions across the tracks and positions along the tracks and tracks; between positions across the tracks when they were nested within positions along the tracks and tracks; between positions along the tracks when they were nested within tracks; and between tracks using five replicates. PERMANOVA version 1.6 by M. J. Anderson from the Department of Statistics, University of Auckland was used for this analysis and this test does not assume normality. It does assume that the observation units are independent of one another, but not the variables in the multivariate case. It also does not assume homogeneity of variances, but is sensitive to heterogeneity of variances and so any differences detected could be due to position or this heterogeneity or a combination of the two. This version allows for multifactorial analysis. No transformation or standardization was used on the raw data and the analysis used Euclidean distances for the dissimilarity metric, which are more appropriate for environmental data than Bray-Curtis (Gosslie and Urban 2007). Nine hundred and ninety nine permutations were made, along with five used as the random seed for permutations. Pair wise comparisons were made for each factor when there was a significant difference. A Bonferroni correction was applied, for example for the level of significance of $p<0.05$ after the application ($0.05/n=4$) this changes to $p<0.0125$ for significance. A permutational analysis of multivariate dispersions (PERMDISP by M. J. Anderson) was used to assess the heterogeneity in the average distances of points from their group centroid using the same details as the PERMANOVA1.6.

Bulk density

The data sets were tested for normality and heterogeneity of variances using the same tests as with compaction and all were not normal and the variances were homogeneous. Transforming the data sets could not rectify this. Permutation based nonparametric multivariate analysis of variance PerMANOVA (Anderson 2005) was then performed to assess the differences in bulk density between positions across and along the tracks with the three tracks as replicates using PCORD 5. This test does not assume normality. The PerMANOVA was set up using the Euclidean (Pythagorean) distance measure for a two-way factorial design, randomisation test and pairwise comparisons. The data set was tested for any interactions between the variables using the statistics from randomisation. Method 1 was used for the analysis of variances when there was an interaction, and Method 2 when there was no significant interaction (Anderson 2005). With the level of significance being $p<0.05$ after applying a Bonferroni correction ($0.05/n=2$) this becomes $p<0.025$ for significance.

Soil water content from soil samples

The soil water data sets were tested for normality and heterogeneity of variances using the same tests as for compaction, and all were not normal and the variances were homogeneous. Transforming the data sets could not rectify this. A three way permutational analysis of variance was used to assess the differences in soil water between depths when they were nested within positions across the tracks and positions along the tracks; between positions across the tracks when they were nested within positions along the tracks; and between positions along the tracks with the three tracks as replicates. PERMANOVA version 1.6 was used for this analysis with the same details as the compaction analysis. With the level of significance being $p<0.05$ after applying a Bonferroni correction ($0.05/n=3$) this changes to $p<0.0167$ for significance.

Soil water content from moisture readers

The moisture reader data sets were incomplete for the three tracks. However, the most complete data sets were analysed for differences between positions across and along the tracks using a Kruskal-Wallis test with a Dunn’s post test or a Mann Whitney test. The rate of drying out of the soil was also determined for this data set by a linear regression of the data from the rainfall event to the end point where the moisture was back to the pre rainfall amounts. The goodness of fit for these lines and the differences in slopes were determined by using a method equivalent to an ANCOVA in Prism 5.

Erosion

The data sets were tested for normality and heterogeneity of variances using the Shapiro-Wilks test Levene test and all were not normal and homogeneous. Transforming the data could not rectify this. A three way permutational multivariate analysis of variance was used to assess the differences in erosion between positions along the tracks when nested within positions across the tracks and tracks, between positions across the tracks when nested within the tracks and between tracks using four replicates. PERMANOVA version 1.6 was used for this analysis with the same details as the compaction analysis. With the level of significance being $p<0.05$ after applying a Bonferroni correction (0.05/n=3) this changes to $p<0.0167$.

Results

3.1 Soil Colour and Texture

The soil in the swale for all the positions was mainly in the 5 to 7.5(YR) yellow red range, with the exception of Track 3 in the undisturbed position where it was 10(YR) (Table 3.2). The soil of Track 1 in the swale for all the positions across the track was a red soil 5(YR). The values of 7.5(YR) are reddish soils and those of 10(YR) can be classed as yellow soils (Table 3.2). Both the soils from the crest and the undisturbed positions exhibited high chroma red and yellow colours (hues), the latter being slightly higher.

Table 3.2 The soil colour description obtained by comparing 48 soil samples from all the positions from across and along the three tracks with Munsell colour charts Tr – tracks, Sw – swale, F/Sl – footslope, Sl – slope, Cr – crest YR - yellow- red spectrum

		Centre			Wheel Rut			Should-er			Undis-turbed	
Tr	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Sw	5YR 4/6	7.5YR 4/4	7.5YR 4/6	5YR 4/6	7.5YR 4/4	7.5YR 5/6	5YR 4/6	7.5YR 4/6	7.5YR 5/6	5YR 4/6	7.5YR 5/6	10YR 5/3
F/Sl	7.5YR 4/6	10YR 5/4	7.5YR 4/6	10YR 4/4	7.5YR 5/6	7.5YR 5/6	7.5YR 5/6	10YR 6/4	10YR 7/3	7.5YR 4/6	10YR 6/6	10YR 6/4
Sl	10YR 6/4	10YR 6/4	10YR 6/6	10YR 5/4	10YR 7/3	10YR 5/4	10YR 6/4	10YR 6/4	10YR 7/3	10YR 6/6	10YR 7/3	10YR 7/3
Cr	10YR 5/3	10YR 7/3	10YR 5/4	10YR 5/3	10YR 7/3	10YR 6/6	10YR 6/4	10YR 6/4	10YR 6/6	10YR 7/3	10YR 7/3	10YR 6/6

The texture of the soil was mainly loamy sand (20 samples), sandy loam (15 samples), sandy clay loam (10 samples), loam (2 samples) and clay loam (1 sample). The swale and footslope in Track 1 were mainly sandy clay loam, while Track 3 was sandy loam and loamy sand in each of these sections respectively. In the slope of Track 1 the soil was loamy sand in the centre and shoulder, the wheel rut was loam and the undisturbed area was sandy loam. Tracks 2 and 3 were mainly loamy sand with the undisturbed area in Track 2 being sandy loam. At the crest, the soils were the same for Tracks 2 and 3 with sandy loam being at the centre and undisturbed positions and loamy sand at the wheel rut and shoulder. Track 1 had loamy sand at the centre and undisturbed positions and sandy loam at the wheel rut and shoulder (Table 3.3).

Table 3.3 Soil Texture from the 48 positions across and along the three tracks using the method of Northcote (1979) Sw – swale, F/Sl – footslope, Sl – slope, Cr - crest C – centre, WR – wheel rut, Sh – shoulder, Un – undisturbed

	Track 1	**Track 2**	**Track 3**
SwC	Sandy clay loam	Sandy clay loam	Sandy loam
SwWR	Sandy clay loam	Sandy clay loam	Sandy loam
SwSh	Sandy clay loam	Sandy loam	Sandy clay loam
SwUn	Clay loam	Loamy sand	Sandy loam
F/SlC	Sandy clay loam	Loam	Loamy sand
F/SlWR	Sandy clay loam	Sandy loam	Sandy loam
F/SlSh	Sandy clay loam	Sandy loam	Loamy sand
F/SlUn	Sandy clay loam	Loamy sand	Loamy sand
SlC	Loamy sand	Loamy sand	Loamy sand
SlWR	Loam	Loamy sand	Loamy sand
SlSh	Loamy sand	Loamy sand	Loamy sand
SlUn	Sandy loam	Sandy loam	Loamy sand
CrC	Loamy sand	Sandy loam	Sandy loam
CrWR	Sandy loam	Loamy sand	Loamy sand
CrSh	Sandy loam	Loamy sand	Loamy sand
CrUn	Loamy sand	Sandy loam	Sandy loam

3.2 Compaction

There were significant differences in compaction (kgf) between the tracks, between the positions along the tracks, between the positions across the tracks and between depths ($p<0.001$) (Table 3.4).

Table 3.4 Results from PERMANOVA 1.6 for the multivariate analysis of the compaction data

Source	**df**	**SS**	**MS**	**F**	**P**
Tracks	2	3150.9	1575.5	62.16	0.001
Along (nested within tracks)	9	8644.7	960.5	37.9	0.001
Across (nested within tracks & along positions)	36	61192.3	1699.8	67.07	0.001
Depth (nested within tracks & along & across positions)	144	148809	1033.4	40.78	0.001
Residual	768	19464	25.3		
Total	959	241260			

Tracks

Pairwise comparison tests among tracks show Track 1 was more compact than Track 3 (t=3.73, p<0.001) (Figure 3.4).

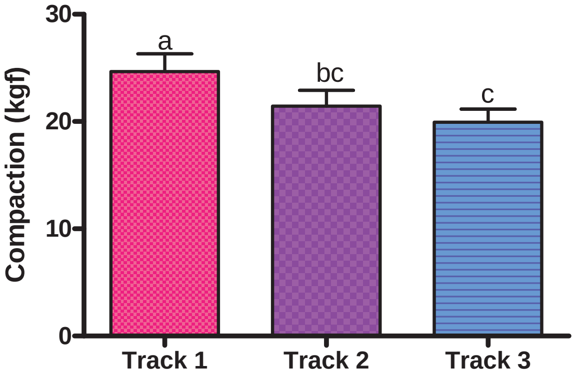

Figure 3.4 Compaction between tracks (n=20, 95%CI) (all depths combined) - letters denote statistical differences at p<0.05 level

Positions along the tracks

Pairwise comparison tests between positions along the tracks when nested within tracks showed the swale to be more compacted than the footslope in Track 1 (p<0.01) and Track 2 (p<0.01), and more than the crest in Track 1 (p<0.001) (Figure 3.5). The footslope and slope were more compacted than the crest (p<0.005 and p<0.008 respectively) in Track 3 (Table 3.5, Figure 3.5). There were differences for the dispersion of replicates for positions along the tracks when nested within tracks PermDisp (p<0.001).

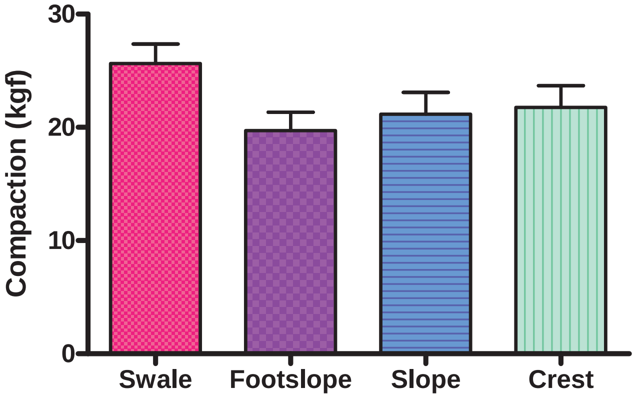

Figure 3.5 Compaction (kgf) along the tracks (swale, footslope, slope and crest) (n=15, 95%CI) (positions across the tracks and depths combined)

Positions across the tracks

The wheel rut was the most compacted position across the tracks with the greatest difference being between the wheel rut and the undisturbed area at all positions along the tracks on all of the tracks except in the slope of Track 1. The centre was the next most compacted position particularly compared to the undisturbed area in the swale and crest of Tracks 2 and 3. The shoulder was more compacted than the undisturbed area in Tracks 2 and 3 in the swale, Track 1 in the slope and Track 3 in the crest (Table 3.5, Figures 3.6, 3.7 and 3.9).

Figure 3.6 Compaction (kjf) across the tracks (centre, wheel rut, shoulder and undisturbed positions) (n=15, 95%CI) (positions along the tracks and depths combined)

Table 3.5 Compaction among the positions across the tracks when nested within the positions along the tracks and within tracks – only showing significant differences from PERMANOVA 1.6 pairwise tests
Sw – swale, F/Sl – footslope, Sl – slope, Cr - crest
C – centre, WR – wheel rut, Sh – shoulder, Un – undisturbed
Tr1 - Track 1, Tr2 – Track 2, Tr3 – Track 3
(* - the differences could be due to the dispersion of replicates for the positions across the tracks when nested within the positions along the tracks and within tracks)

	SwC	**SwWR**	**SwSh**	**F/SlC**	**F/SlWR**	**SlC**	**SlWR**	**SlSh**	**CrC**	**CrWR**	**CrSh**
SwWRTr1	<0.002										
Tr2											
Tr3											
SwShTr1		<0.002									
Tr2											
Tr3		<0.008									
SwUnTr1		<0.003									
Tr2	<0.002*	<0.001	<0.001								
Tr3	<0.001	<0.001	<0.002								
F/SlShTr1					<0.006						
Tr2					<0.003*						
Tr3				<0.003*	<0.001						
F/SlUnTr1					<0.001						
Tr2					<0.001*						
Tr3				<0.001*	<0.001						
SlWRTr1											
Tr2						<0.007					
Tr3						<0.002					
SlShTr1							<0.003				
Tr2							<0.002*				
Tr3							<0.004				
SlUnTr1								<0.001			
Tr2						<0.004	<0.001*				
Tr3							<0.001				
CrShTr1										<0.003	
Tr2										<0.001	
Tr3											
CrUnTr1										<0.001	
Tr2									<0.009	<0.001*	
Tr3									<0.001	<0.001	<0.002

Overall, the differences in compaction were largely due to the positions across the tracks. However, the differences were less reliably attributed to the positions across Track 2 where there was some variability in the data set as shown by the high dispersion of replicates Permdisp (p<0.01).

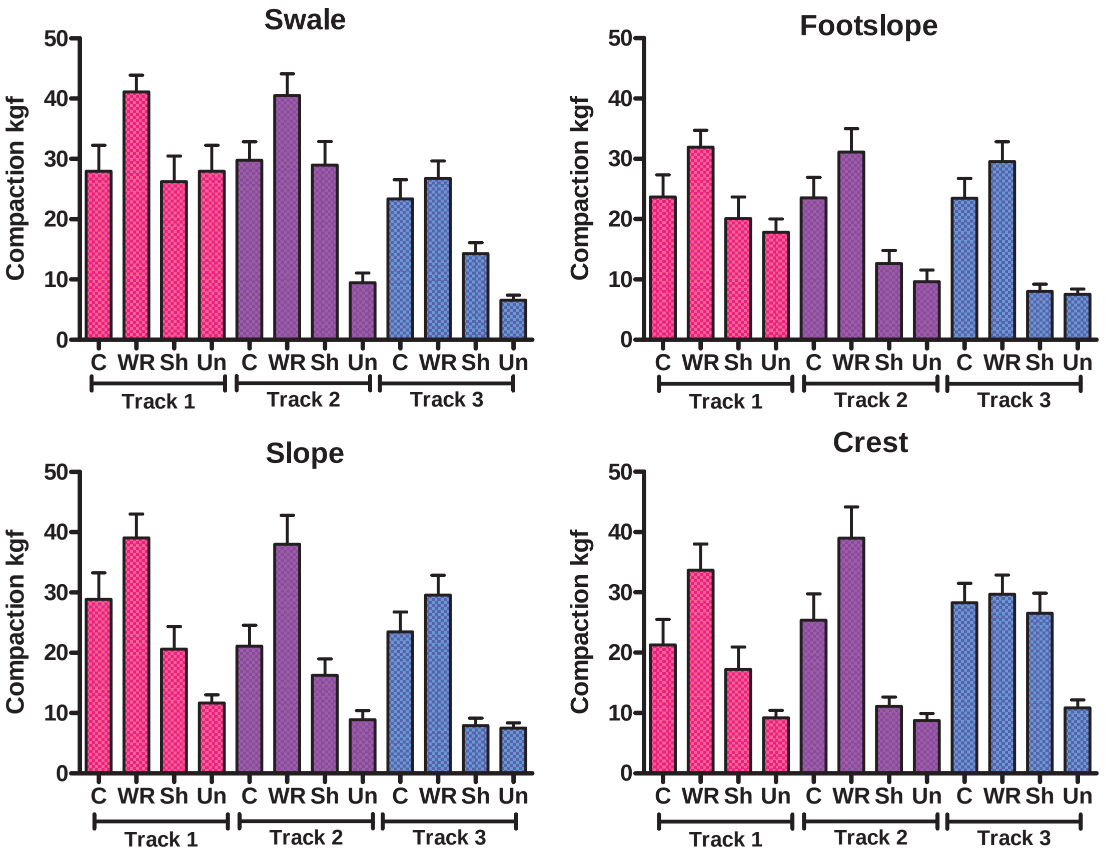

Figure 3.7 Compaction (kgf) for positions across the tracks (C – centre, WR – wheel rut, Sh – shoulder, Un – undisturbed) at each position along the tracks (swale, footslope, slope and crest) (n = 5, 95%CI) (all depths combined)

<u>Depths</u>

The wheel rut was more compacted at each of the depth levels than all the other positions across the tracks, particularly near the surface. In the undisturbed area the compaction was less than the other positions at all the depth levels except at the surface where it was the same as centre and shoulder. The centre and shoulder had similar patterns of compaction to each other in the shallower parts of the soil profile and then the centre became more compacted than the shoulder at deeper levels. (Table 3.6, Figures 3.8 and 3.9).

Table 3.6 Tests for significant differences PERMANOVA 1.6 (p<0.05) in compaction among levels of the factor depth when nested within the positions across the tracks, positions along the tracks and tracks
C – centre, WR – wheel rut, Sh – shoulder, Un – undisturbed, Sw – swale, F/Sl – footslope, Sl – slope, Cr – crest
Tr 1 – Track 1, Tr2 – Track 2, Tr3 – Track 3
1:0-3 cm, 2:6-15 cm, 3:18-24 cm, 4:27-45 cm

	SwTr1	**F/SlTr1**	**SlTr1**	**CrTr1**	**SwTr2**	**F/SlTr2**	**SlTr2**	**CrTr2**	**SwTr3**	**F/SlTr3**	**SlTr3**	**CrTr3**
C	2>1	2>1	2>1	2>1		2>1	2>1	2>1	2>1	2>1	2>1	2>1
C	3>1,2	3>1	3>1,2	3>1,2	3>1	3>1*,2*	3>1,2	3>1	3>1,2	3>1	3>1,2	3>1,2
C	4>1,2,3	4>1,2	4>1,2	4>1,2,3	4>1	4>1*,2*	4>1,2	4>1,2,	4>1,2	4>1	4>1,2,3	4>1,2
WR	2>1	2>1	2>1	2>1	2>1	2>1	2>1	2>1	2>1	2>1	2>1	
WR	3>1	3>1	3>1	3>1,2	3>1	3>1*	3>1,2	3>1,2	3>1	3>1,2	3>1,2	3>1
WR	4>1,3	4>1	4>1,2,3	4>1,3	4>1	4>1*,2*	4>1,2	4>2	4>1	4>1,2	4>1,2,3	4>1,2
Sh	2>1	2>1		2>1	2>1		2>1	2>1	2>1		2>1	2>1
Sh	3>1,2	3>1,2	3>1	3>1,2	3>1		3>1,2	3>1	3>1		3>1	3>1
Sh	4>1,3	4>1,2,3	4>1	4>2,3	4>1,2	4>1	4>1,2	4>1,2	4>1,2		4>1	4>1,2
Un	2>1	2>1	2>1		2>1		2>1	2>1	2>1	2>1	2>1	2>1
Un	3>1	3>1	3>1,2	3>1	3>1			3>1,2	3>1	3>1		3>1
Un	4>2,3	4>2	4>1,2	4>1,2	4>1,3	4>1	4>1,2	4>1,2	4>1,2,3	4>1,2	4>1,2,3	4>1,2

* The test for dispersal of replicates for depth nested within the positions along and across the tracks and the tracks, showed differences (p<0.001), mainly in Track 2 at the footslope in the centre and wheel rut (Table 3.5).

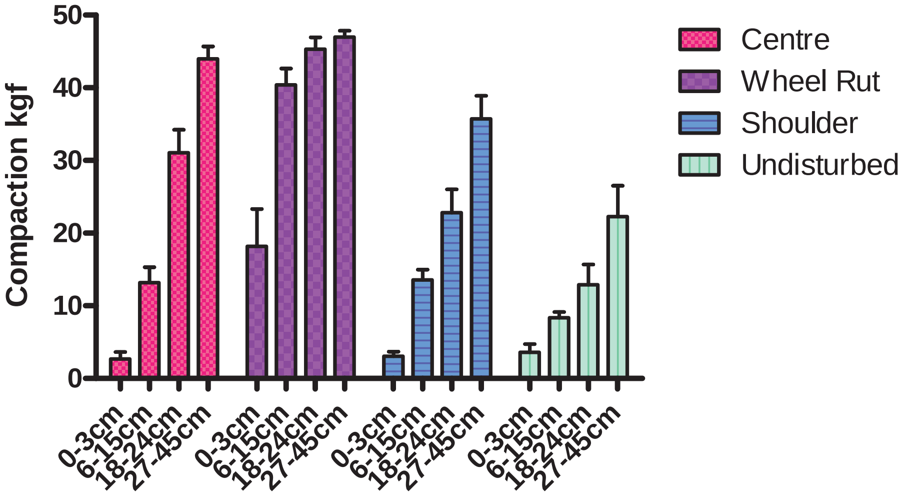

Figure 3.8 Compaction at four depth levels for the positions across the tracks at the most compacted position along the tracks i.e. the swale (n = 15, 95%CI) (3 tracks combined)

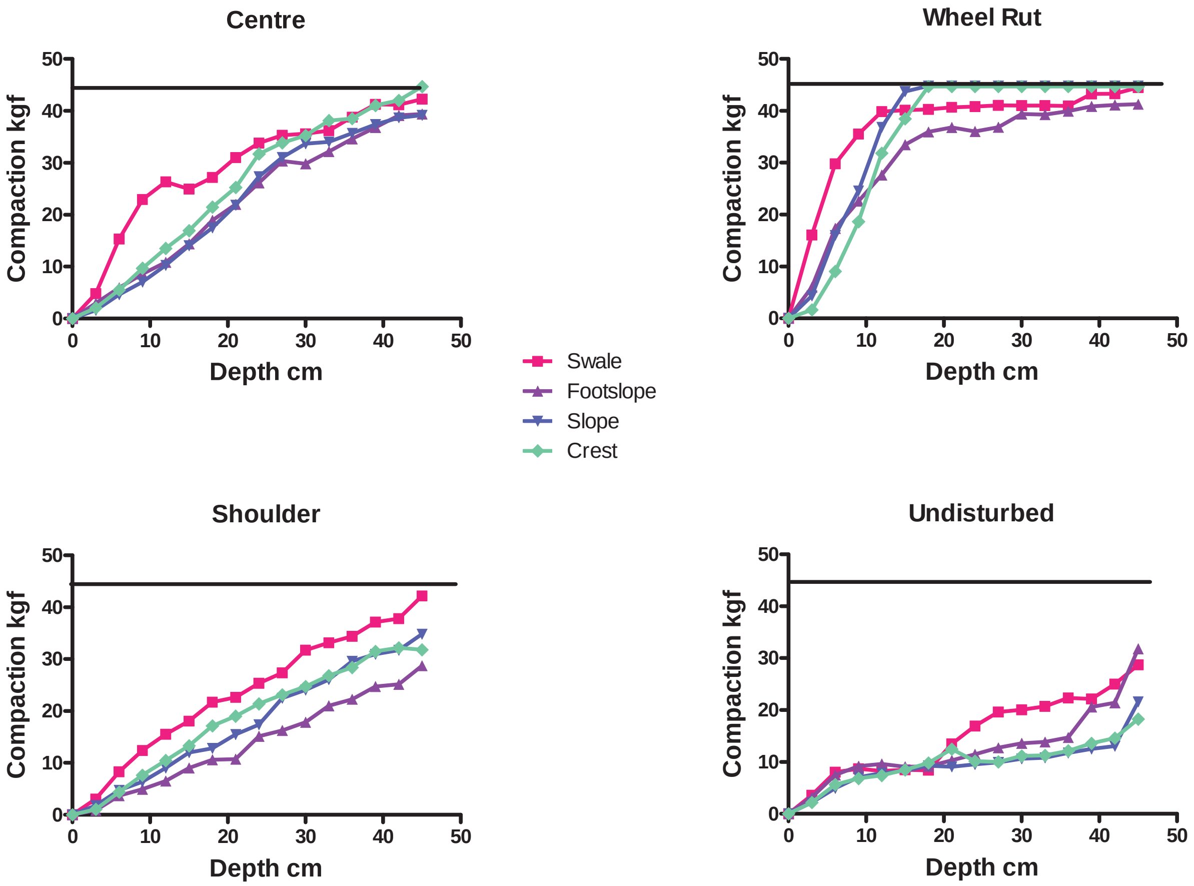

Figure 3.9 Compaction (kgf) for positions along the tracks at each position across the tracks (n = 15, 95%CI) (3 tracks combined) with the black line indicating the maximum compaction the Penetrometer was able to read accurately

Summary of Compaction Results

In summary the greatest difference between the disturbed positions and the undisturbed area occurred in Track 3, particularly in the swale where the disturbed positions were more compacted than the undisturbed positions, while on Track 1 in the swale the centre and shoulder had similar compaction to the undisturbed. In Track 3 at the crest there was greater compaction at the centre and shoulder on the track than the other two tracks adding to this larger difference between the disturbed and undisturbed areas.

3.3 Bulk density

There were differences in the bulk density between the positions across the tracks PerMANOVA ($F_{3,47}$=4.25, $p<0.01$) with the wheel rut having a higher bulk density than the centre ($t=3$, $p<0.01$), the shoulder ($t=2.85$, $p<0.01$) and the undisturbed area ($t=1$, $p<0.01$) (Figure 3.10), but there were no differences between the positions along the tracks and no interactions between the two factors.

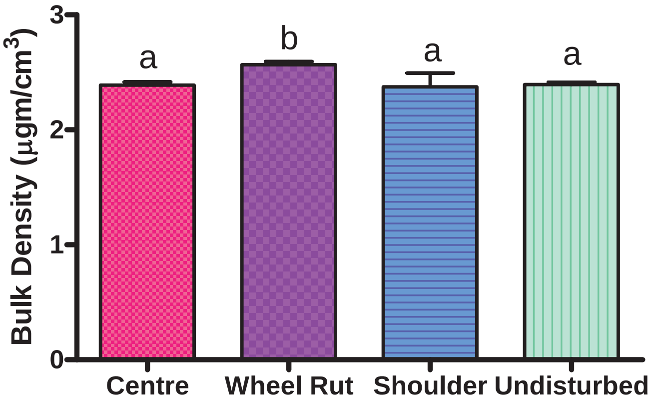

Figure 3.10 Bulk density (µgm/cm^3) for positions across the tracks (n = 3, 95%CI) (positions along the tracks combined) – letters denote differences at ($p<0.01$)

3.4 Soil water content

3.4.1 Soil Samples

PERMANOVA 1.6 analysis of soil water content showed no significant differences between the positions across or along the tracks or depths, but there were some differences in the pair-wise comparisons in the swale with the shoulder having more moisture than in the undisturbed area ($t=2.4$, $p<0.05$). In the footslope the wheel rut had more soil water than the shoulder (t=4.9, p<0.01) and the undisturbed area (t=4.37, p<0.01). In the crest the wheel rut had more soil water than the shoulder (t=2.53, p<0.05) (Table 3.7, Figures 3.11, 3.12).

Table 3.7 Results from PERMANOVA 1.6 for the soil water from the positions along the tracks; the positions across the tracks when nested within the positions along the tracks; the depth levels when nested within the positions along and across the tracks

Source	df	SS	MS	F statistic	P value permutational
Along	3	3.9	1.3	1.58	0.18
Across (Along)	12	13.1	1.1	1.32	0.21
Depth(AlongxAcross)	64	38	0.6	0.74	0.95
Residual	160	132.1	0.8		
Total	239	188.1			

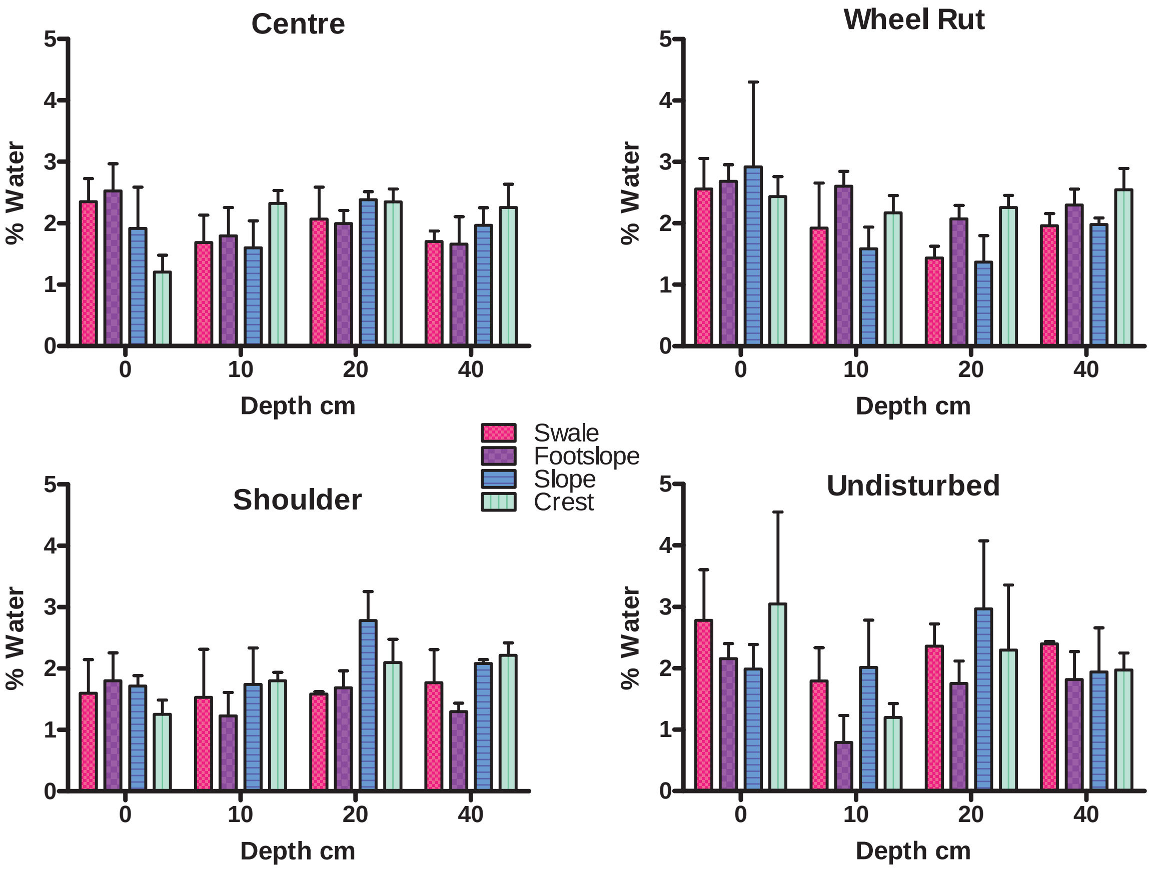

Figure 3.11 Soil water content in soil samples from the positions across the tracks (n = 3, 95%CI)

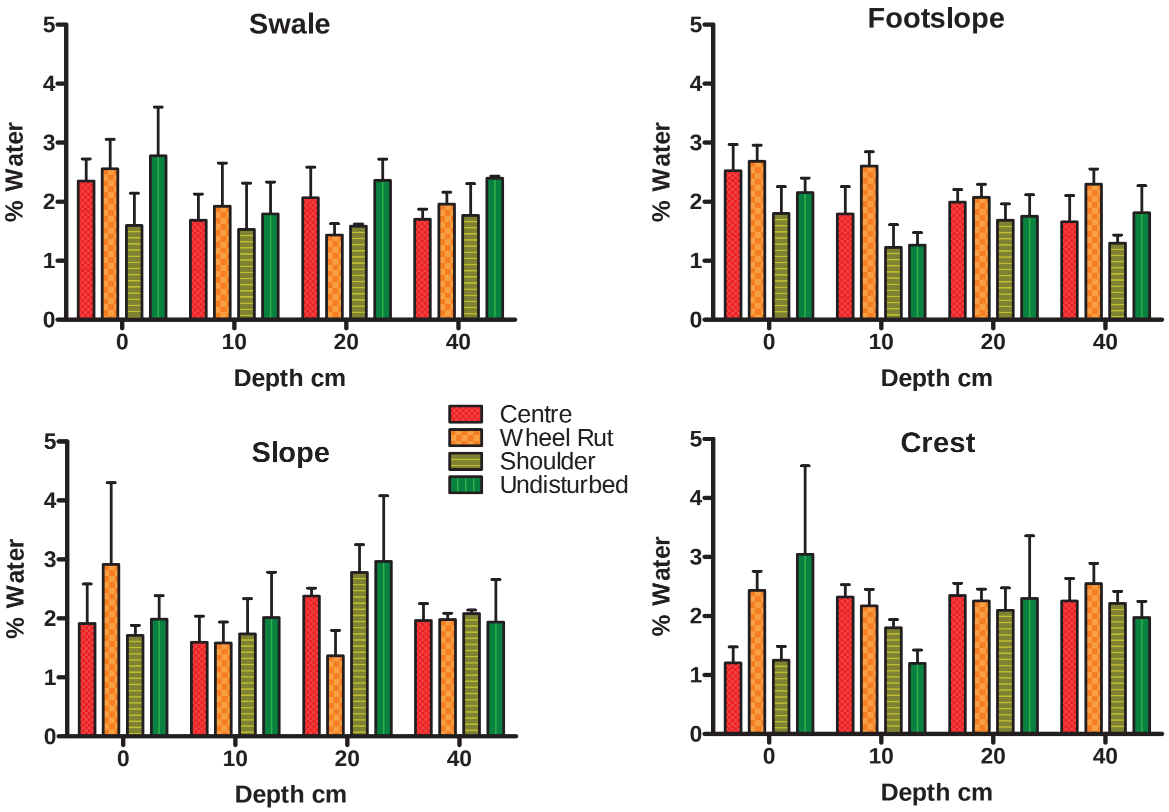

Figure 3.12 Soil water content in soil samples from the positions along the tracks (n = 3, 95%CI)

3.4.2 Moisture Readers

In Track 1 there was a significant difference in soil water content in the positions across the tracks in the swale using Kruskal-Wallis ($p<0.001$). The soil water content was higher in the wheel rut than the shoulder in Dunn's post test ($p<0.001$), and the undisturbed area in the open had more soil water than the shoulder in Dunn's post test ($p<0.001$) (Figure 3.13a)). There was a significant difference in soil water content between the positions across the tracks in Track 3 in the swale Kruskal-Wallis ($p<0.001$), in the slope ($p<0.05$) and in the crest ($p<0.001$) (Figure 3.13b)). In the swale the centre had more soil water than the shoulder in Dunn's post test ($p<0.001$) and more soil water than the sample from under a tree in the undisturbed area Dunn's post test ($p<0.01$); the wheel rut had more soil water than the shoulder Dunn's post test ($p<0.001$), more soil water than the undisturbed area in the open

Dunn’s post test (p<0.05) and more soil water than the undisturbed area under a tree Dunn’s post test (p<0.001). In the slope the centre had more soil water than the shoulder in Dunn’s post test (p<0.01). In the crest the wheel rut had more soil water than the centre in Dunn’s post test (p<0.01) and more soil water than in the undisturbed area under a tree in Dunn’s post test (p<0.001) (Figure 3.13b)).

In Track 3 in the swale the wheel rut dried out faster than the centre ANCOVA (p<0.01), shoulder ANCOVA (p<0.001) and the undisturbed area in the open ANCOVA (p<0.01). The wheel rut also dried out faster than the undisturbed area under the tree in the crest ANCOVA (p<0.001) (Figure 3.13b).

In Track 3 in the positions along the tracks in the centre there were differences in the soil water content Kruskal-Wallis (p<0.01), with the swale with more soil water than the slope Dunn’s post test (p<0.01) and the slope had more soil water than the crest (p<0.05) (Figure 3.14). There was more soil water in the swale than the crest in the wheel rut Mann Whitney test (p<0.01) and in the undisturbed area in the open Mann Whitney test (p<0.001) (Figure 3.14).

In Track 3 the swale dried out faster than the slope in the undisturbed area in the open ANCOVA (p<0.05) and under a tree ANCOVA (p<0.05) (Figure 3.13).

To summarise, the data showed less water content in the sections going up Track 3 from the swale to the crest for all the positions across the tracks for all the times and the wheel rut had more water than the centre, shoulder and the undisturbed area under a tree, the shoulder had more than the undisturbed area in the open and the undisturbed area in the open had greater water content than in the undisturbed area under a tree (Figures 3.13a), b) and 3.14).

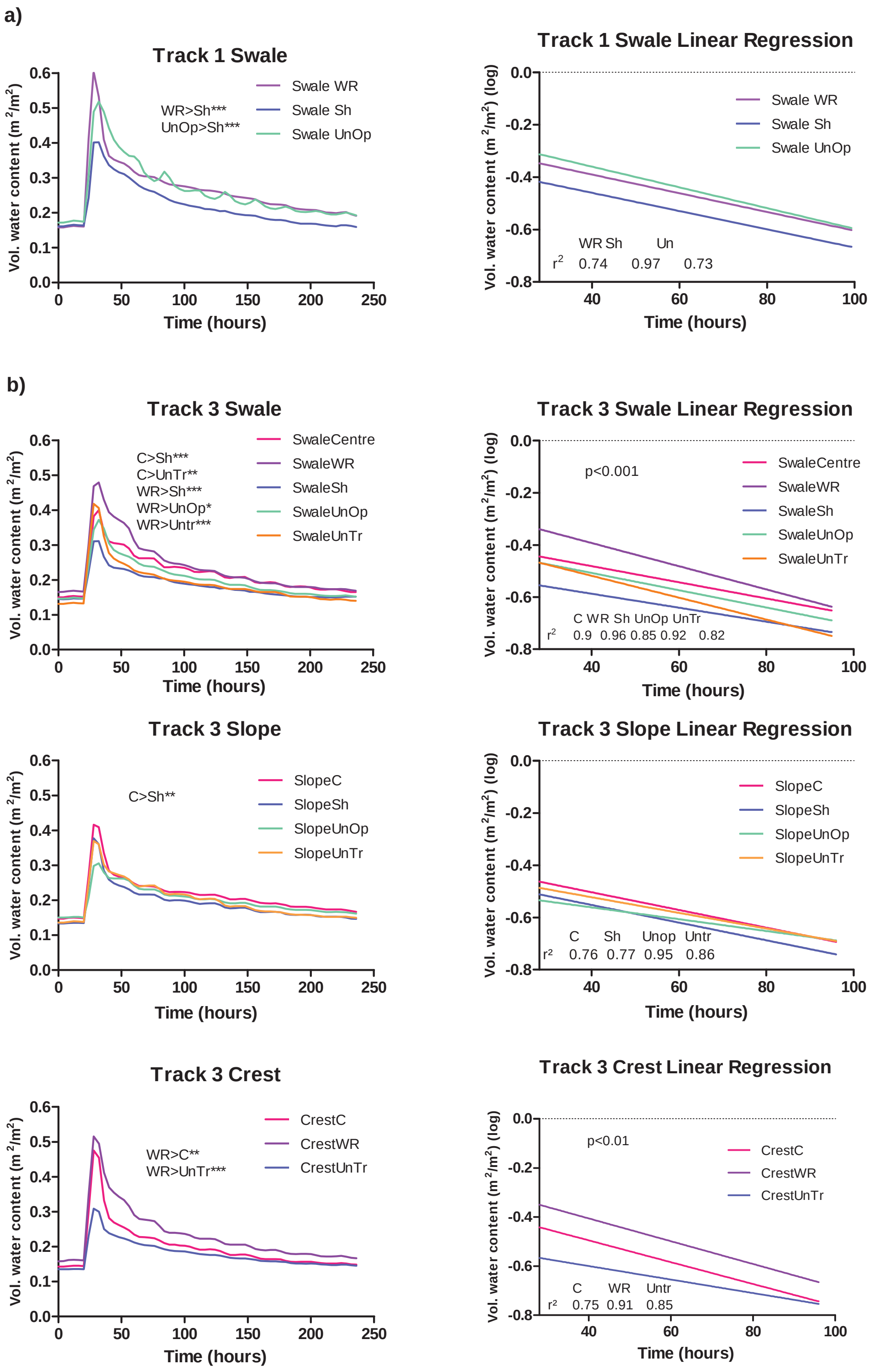

Figure 3.13 Soil water for a) Track 1 swale and b) Track 3 for the positions along the tracks for C – centre, WR – wheel rut, Sh – shoulder, UnOp – undisturbed in the open, UnTr – Undisturbed under a tree. The lines were tested for best fit resulting in r^2 values, which were all over 0.75 and all passed the test for linearity

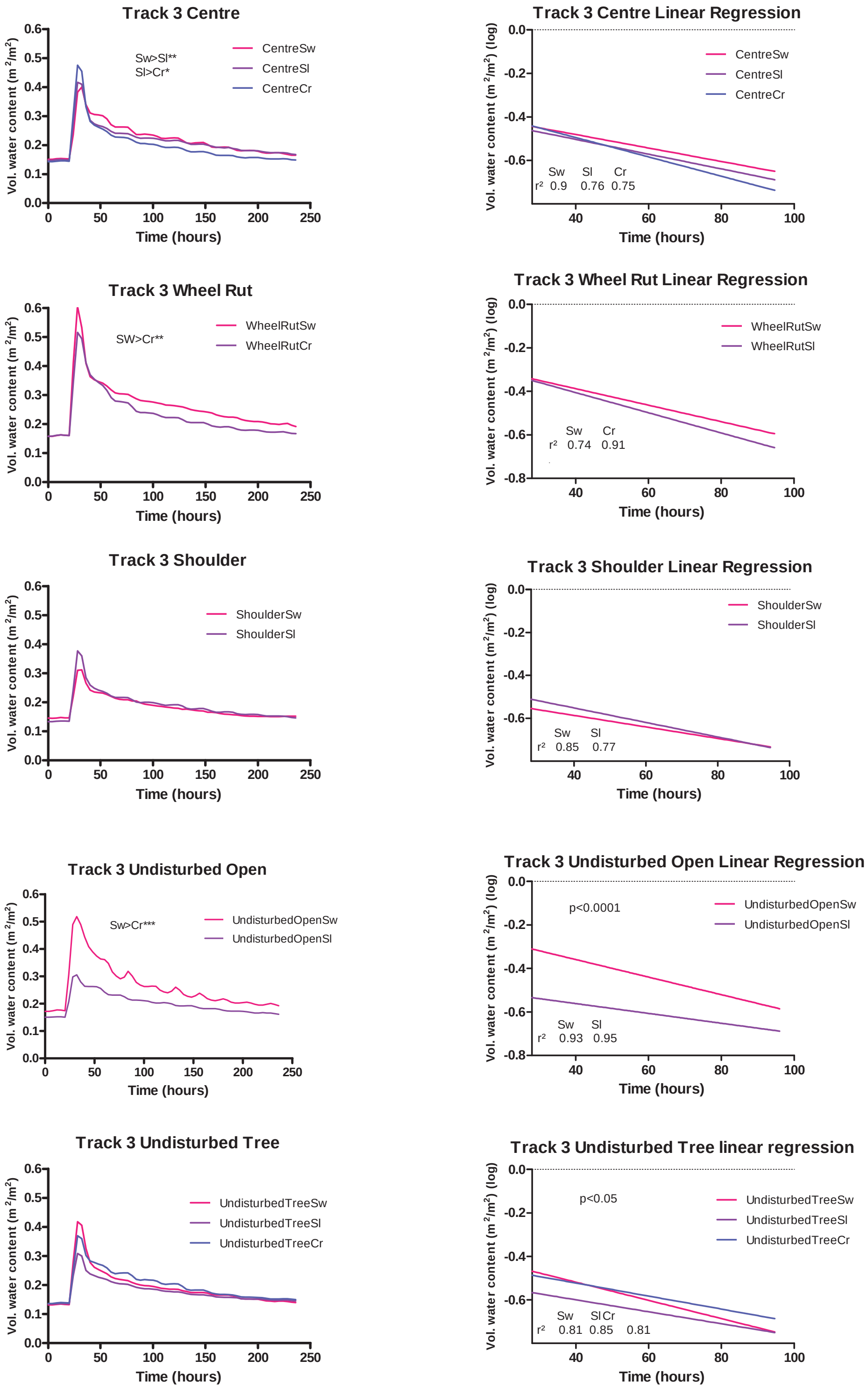

Figure 3.14 Soil water for Track 3 for all the positions across the tracks for the Sw – swale, Sl – slope and Cr – crest. The lines were tested for best fit resulting in r^2 values, which were all over 0.74 and all passed the test for linearity.

3.5 Erosion

Erosion, differed between the disturbed positions and the undisturbed positions when nested within tracks and the positions along the tracks PERMANOVA 1.6 ($F_{9,71}$=5.2, p<0.002) (Table 3.8). There was more soil collected in trays in the disturbed area than in the undisturbed area in Track 1 in the swale (t=7.7, p<0.05), slope (t=4.17, p<0.05) and crest (t=5.53, p<0.05) and in Track 2 in the swale (t=2.23, p<0.05), slope (t=1.99, p<0.05) and crest (t=3.59, p<0.05) (Figure 3.15).

Track 1 in the slope had more soil deposited than in the swale (t=2.3, p<0.05) (Figure 3.16).

There was a significant diffeence between the tracks PERMANOVA 1.6 ($F_{2,71}$=10.3, p<0.001) (Table 3.8) with Track 2 having more soil deposited than Track 1 (t=3.7, p<0.05) and Track 3 (t=2.87, p<0.01) (Figure 3.15).

Table 3.8 Results from PERMANOVA 1.6 for the erosion data for the tracks, the positions along the tracks nested within tracks and the positions across the tracks when nested within tracks and positions along the tracks

Source	df	SS	MS	F statistic	P value permutational
Tracks	2	315392	157696	10.3	0.001
Along (Tracks)	6	47418	7903	0.5	0.804
Across (Tracks and Along)	9	725105	80567	5.2	0.002
Residual	54	830414	15378		
Total	71	1918329			

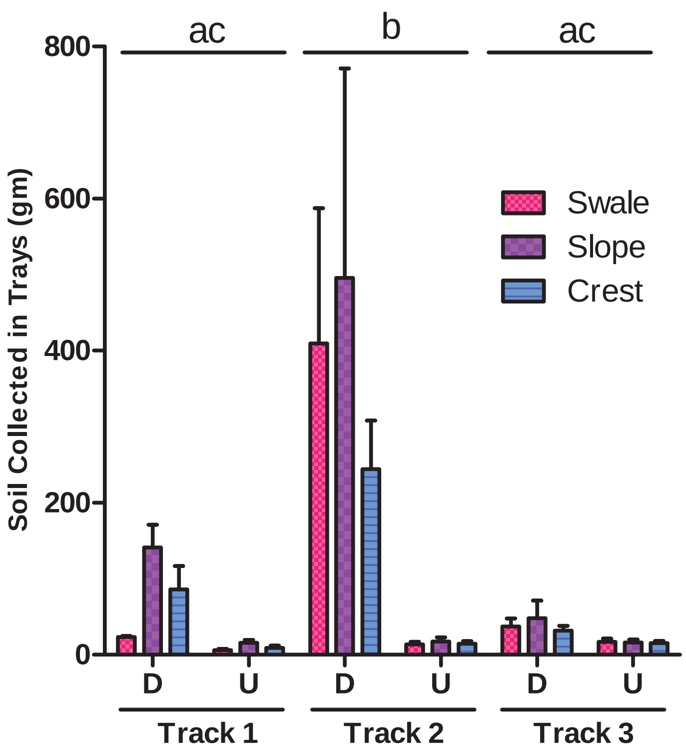

Figure 3.15 Weight of soil collected in trays for the 3 Tracks , D – disturbed, U – undisturbed – letters denote differences using PERMANOVA 1.6 ($p<0.05$)

Discussion

The clearance of access tracks in this site produced significant changes in the environmental characteristics across the landscape. The initial mechanism that produced the changes in the function of the system along the tracks was the clearing of vegetation. After this clearance, soil compaction was exacerbated by the subsequent use of the tracks by off road vehicles carrying out the operations associated with mineral exploration. This use involved the tracks being traversed twice by a drill rig (one return trip) and a number of times by support 4WD vehicles (Drown 2003). Compaction was greater in the wheel rut than the other positions across the tracks, as was the bulk density. In a large number of instances soil water content in the top layer of soil was higher in the more compacted areas, such as the wheel rut. Erosion, as shown by the amount of soil movement, was greater in the disturbed area than in the undisturbed area. In terms of the topographic position along the tracks the swale was more compacted than other positions along the tracks, but the bulk density was not greater at this position. There was slightly more soil water content in the swale than the crest in a number of positions across the tracks. There were also some differences between tracks with Track 1 being more compacted than the other two tracks and Track 2 having more soil movement than the other tracks. There was some variability in the data, particularly in Track 2.

The largest differences in the parameters studied were detected across the tracks. The wheel rut was more compacted than any other position resulting from the use of the tracks by wheeled vehicles. The centre and shoulders of the tracks were both more compacted than the undisturbed area. The centre was the result of the initial rolling and the shoulder was formed from the soil being pushed to the side as the track was rolled, and so was less compacted than the other positions across the tracks. This soil compaction has been shown by other studies to be one of the most common and important effects of off road activities (Liddle 1997).

The topographic and edaphic characteristics of the system were two factors determining the severity of the changes observed. The soil in the undisturbed area of Track 1 had a higher compaction score than the undisturbed areas of the other two tracks. The differences in compaction between tracks could have been due to both, the positions across and along the tracks, and the depth combined. However, there was some variability in the data. This was particularly evident in the compaction at depths 0-3 cm and 6-15 cm levels which were more compacted in Track 1 than Tracks 2 and 3. Topographically the tracks had different patterns of compaction in the undisturbed area with Track 1 having less compaction at the crest than the swale while the other two tracks showed little difference. The swale in the disturbed area was generally greater in compaction than the other positions along the slope, except Track 3, which showed a higher compaction on the tracks at the crest than at the swale.

There were differences between the tracks in soil characteristics. Within the study area of Baggy Green the soil was sandier going in a northerly direction. Track 3 was the northernmost track it was sandier than Track 2, which was sandier than Track 1, the southernmost track. Track 1 soil had higher clay content than that of Track 3, which was mainly loamy sand. The susceptibility to compaction of different soil types varies considerably (Webb *et al*. 1978). Loamy sands were most susceptible to density increases under loading, while soils consisting of particles of uniform size, such as dry sands and clays, are the least susceptible to compaction (Bodman and Constantin 1965, Webb 1983, Lovich and Bainbridge 1999). The loamy sand of Track 3 was less uniform and coarser than the soil in Track 1 this could explain the larger impact due to compaction in Track 3. The red colour of soils is due to the oxidation of iron. All soils were oxidising, but there was a pattern of the "intensity" of a colour, i.e. the chroma, decreasing on going down the track to the swale. This decrease indicated the soil becoming more oxidising showing that more chemical weathering was taking place (Peverill *et al.* 1999). Thus, a corresponding increase in nutrient availability would be expected at this position in the swale. The soil character of colour changed down Track 1 from 10(YR) at the crest to 5(YR) at the swale along with the texture changing from coarse to fine, indicating an increase in iron oxide and clay content (Hradil *et al*. 2003), whereas the other two tracks changed from 10(YR) to 7.5(YR) indicating less clay in the swale than Track 1. The amount of usage of the tracks by off road vehicles could have been a factor in the differences between the tracks, however the density near the soil surface increases in a logarithmic fashion as the number of vehicle passes increases (Iverson *et al*. 1981). This indicates that the greatest change in soil properties occurs during the first few passes, and so the effect of usage differences would be reduced, particularly as this change per pass decreases as the number of passes increases (Webb 1982).

The bulk density was greater in the wheel rut than the other positions across the tracks, and this was also the area of greater compaction. This is due to surface pressure causing bonds of aggregating agents in the soil being compromised resulting in the structural units falling apart (Kozlowski 1999) and smaller pore spaces in the soil forming. This can substantially affect the soil hydraulic properties in terms of a reduction in the infiltration of the soil (Iverson *et al*. 1981). The result of this is that moisture remains in this denser soil instead of filtering through the soil, and if the density is too great the water will just run off. Assouline (2005) showed that changes in the soil bulk density can account for the major effect of compaction on the water retention curve (WRC), and that this variable can be used to predict the WRC of compacted soils. This in turn affects the penetration potential of roots in plant growth (Kozlowski 1999).

On the three tracks there was less water content at the shoulder than other positions in the disturbed area. A possible explanation for this is that there was water flow down the sides of the wind rows into the wheel rut, and the other side into the undisturbed area next to the track. Water also would flow down the sides of the less compacted central position, resulting in the channelling of water into the wheel ruts where it is compacted and can flow unhindered down the slope. This scenario of water flows was supported by the higher water content of the soil in the wheel rut than all the other positions particularly in the top layer of the soil. The moisture readers showed that the wheel rut dried out faster than the other positions possibly due to the water being held in the soil closer to the surface and therefore having a higher evaporation potential. The undisturbed area had more water than the shoulder and centre and in terms of the topography of the area the swale had more water than the slope in the undisturbed area. This would be where the water collected with no place to run off and would be held in the top layers due to higher compaction in the swale than along the slope. The water in the soil was held in the more compacted areas for longer than in the undisturbed areas where it filtered down through the soil to the deeper layers much quicker. This has been found in other studies where compacted soil on routes used by off road vehicles had poor infiltration of water (Brooks and Lair 2005) and also in deserts where the surface storage of water for more than a few hours occurs only in low sites receiving runon, with low permeability (Noy-Meir 1973).

The higher the clay content in the soil the higher the compaction potential and while water is held in the upper layers such as in the swale and the wheel rut these positions could be more vulnerable to increasing compaction if there is usage while the soil is wet (Webb 1982). As Adams *et al*. (1982) found in their experiments in the Mojave Desert driving a four wheel drive vehicle compacted the soil to a greater depth when driven on wet soil than on dry soil. Adams *et al*. (1982) also found that as the soil dried out the rate of increase of soil strength was much greater in the compacted areas than in the undisturbed area. These two processes could therefore, further increase the compaction in the areas already compacted.

In the present study the moisture readers showed the crest on the tracks absorbing more water initially and drying out at a faster rate than the crest in the undisturbed area. This initial higher reading was possibly due to the greater exposure of the soil and lack of vegetation to intercept the rainfall. Subsequently the drying out rate could be due to this water either running down the slope, or infiltrating to lower layers. The rate of runoff on the tracks would likely to be higher down the slope than in the undisturbed area. Particularly as on the undisturbed slope water runoff would follow an indirect flow path as it gets diverted by numerous small topographic obstructions, such as rocks and plants. This would result in the flow slowing down enough for small amounts of material to be deposited gradually at the sites of vegetation (Iverson *et al*. 1981).

The lack of cover of dead and living vegetation can increase rain impact, and so increase runoff. This increase was found by Tadmor and Shanan (1969) in their study where the eradication of natural vegetation from runoff plots increased annual runoff threefold from 7% to 21% of annual rainfall. They also found the vegetation cover increased the infiltration rates by 40–50%. The removal of vegetation and compaction also may have a combined effect resulting in increased diurnal soil and air temperature fluctuations (Luckenbach and Bury 1983). There are, therefore, different transport processes taking place in the disturbed areas compared to the undisturbed areas.

There was a larger movement of soil along the tracks down the dune than in the undisturbed area, particularly in Track 2, which had a higher elevation than the other tracks. From observations there was very little soil movement in the first two years (2005 and 2006) of the study, probably because of the lack of intense rainfall events. There was a drought in the second year (2006) which would have dried out the soil. When there was heavy rain in the beginning of the third year (2007) of the study, i.e. when the soil movement was measured, there would have been a large amount of water movement across the landscape due to the topography of the region. This reflects the situation in the Mojave Desert where Iverson *et al*. (1981) found that soil erosion may only occur at intervals of tens of years in undisturbed areas with 40-60 mm/hr for 20 mins of rainfall. In the areas impacted by off road vehicles they found that runoff occurs with rainfall of less than 10mm/hr resulting in more frequent erosion events. The soil that collected in the present study in the containers indicated that there had been sediment movement along with this runoff. It is unlikely that this soil movement was the result of wind movement. Water erosion is the result of occasional intense rains while wind erosion can occur as a result of severe wind events it is more likely to be from more frequent bursts of wind. Water movement is unidirectional down a slope and irreversible and wind movement is two dimensional and can be partially irreversible.

The largest amount of soil was collected in the containers in the disturbed area of Track 2 indicating that the runoff was the greatest along this track. The water content of the soil from the moisture readers of Track 2 was not included in the data sets due to missing values and so any differences in infiltration between the tracks are not known. The soil texture was sandier than Track 1, but less sandy than Track 3 and it was less compacted than Track 1 and not different from Track 3. The increased erosion was probably due to this track having the greatest slope of the three tracks i.e. 16.85^0 compared to 2.28^0 for Track 1 and 6.95^0 for Track 3.

The impacts to the mallee ecosystem caused by linear disturbances, such as tracks could persist for decades after use if no rehabilitation is carried out. This has been observed in logging skid trails 40 years old with soil 20% more compacted than in undisturbed soil nearby (Vora 1988). Similarly, in an Australian forest there was little recovery of compacted soils for at least seven years (Cheatle 1991), and recovery has been shown to vary with the depth of the compacted layer with, in some cases, no recovery evident after 8.5 years for 15-23 cm or 23-30 cm depths (Thorud and Frissell 1976).

Overall, it has become apparent that there are strong spatial dependencies due to topographic features in relation to the physical variables of soil structure and water dynamics. Soil structural changes were caused by compaction of the soil as a result of the movement of vehicles along the mineral exploration tracks. The consequence of this compaction and the clearing of vegetation determined the differences in water dynamics between the disturbed area and the undisturbed area. Soil characteristics, both due to the topography and differences between the tracks due to their position in the landscape had an influence on the amount of impact due to compaction and erosion. This complex interaction could be researched further by studying tracks in a number of different environments particularly in terms of elevation and soil characteristics. A more complete picture of the mechanisms of change to these physical characters of the environment could be obtained by monitoring seasonal changes of the water dynamics using moisture probes attached to readers placed at different depths and for longer periods at all the positions. The changes in surface and soil moisture levels are important as they could also lead to changes in decomposition rates, seedbank characteristics and changes in habitat for ground dwelling fauna (Saunders *et al*. 1991). More knowledge is needed on the mechanisms of soil movement in relation to linear disturbance in the semi-arid zone in mallee dunal country as this has been shown in this study to possibly be an important feature of the landscape processes.

These changes in transport processes across and through the landscape where tracks are formed, could possibly result in subsequent changes in ecosystem functioning due to the disruption of the pattern of nutrient recycling and chemical characteristics. The density may increase even when a road is not used, as Helvey and Kochenderfer (1990) found in their study of the soil density and water content of two unused forest roads. As the most compact soils occur in the top layers that normally contain most roots, the physical characteristics of this layer examined in this chapter would influence the composition of the vegetation.

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Chapter 4 Effects of disturbance on the landscape and ecosystem processes - Spatial heterogeneity in nutrient distribution

Introduction

The amount and distribution of nutrients in the soil and organic matter, along with pH and conductivity, all have a possible effect on the biomass and composition of vegetation (Saunders *et al*. 1991). As Aerts and Berendse (1988) showed with the addition of nitrogen, phosphorous and potassium on a mixed vegetation of *Erica* sp. and *Molinia* sp., the biomass of *Erica* sp. decreased and the *Molinia* sp. increased, with phosphorous being the main contributing factor. The patch dynamics observed in arid conditions where the composition of the vegetation is changed in areas of high nutrients under tree canopies also illustrates the influence of nutrients (Facelli and Brock 2000). The soil pH has been correlated with the species composition in a tropical montane system (Sollin 1998). Increased soluble salts in the root zone can have a detrimental effect on growth (Donahue et al. 1983), but this depends on the plant species (Brady and Weil 1996). Nutrients can be redistributed via a series of mechanisms that are controlled by topography, plant cover and soil properties, such as texture and structure (Hook *et al*. 1991, Ludwig and Tongway 1995). Disturbances are likely to affect at least some of these factors. Spatial heterogeneity of nutrients can contribute to the functional structure of the ecosystem. Factors that modify the pattern modify the plant community and ecosystem functions. Recovery after disturbance may be impossible if some of these changes are strong and irreversible. In this chapter the effect of the clearing of vegetation for access tracks on the distributions of nutrients in the soil, organic matter, the pH and conductivity are explored.

Spatial variability of soil water redistribution in natural ecosystems causes patchiness of vegetation and nutrient availability (Noy-Meir 1973). Nutrient transport by soil and water results in an accumulation down slope, in local depressions and around logs and plants. These areas where nutrients are concentrated are particularly important sources in soils which have a very low nutrient status, as is the case for most soils of Australia (Beadle 1966). The size of these patches and their topographic position are important features that determine the impact of disturbance in these environments (Ludwig and Tongway 1995). These patches can have different scales from groves of trees and individual trees; large shrubs and clumps of smaller shrubs, and within more open groves; shrubs, fallen logs, clumps of grasses, and at a smaller scale again; individual grasses forming tussocks and all of these result in sinks rich in resources (Ludwig and Tongway 1995). While Ludwig and Tongway’s (1995) study was conducted in *Acacia aneura* (mulga) woodlands in eastern Australia, the idea of different scales of organisation also applies in mallee systems, where the structure of the plant community consists of heterogeneous, but continuous, woody plant cover. Different shrub species in the arid zone of Australia and the patchiness in the distribution of nutrients associated with them could affect the growth of annual plants under them (Facelli and Temby 2002). There is little information on the small scale spatial variability in mallee or on the impact of disturbance. While seventy percent of the Australian continent consists of arid and semi-arid ecosystems characterised by patchy vegetation (Noy-Meir 1973), there is the possibility of these patches acting as "islands of fertility" (Kellman 1979). Noble *et al*. (1996) supported this in their studies in mulga country in semi-arid eastern Australia where soils under patches of vegetation had greater organic matter, nutrients and microbial activity than elsewhere. These unique and dynamic microenvironments are a product of both physical and environmental factors (Tongway and Ludwig 1994, Facelli and Brock 2000, Facelli and Temby 2002), with the topography determining the fluvial and aeolian erosional/depositional processes (Ludwig and Tongway 1995).

There have been only a few studies on the effects of clearance of vegetation as a disturbance in these environments. Those that have been conducted show that sites of high nutrient concentration can be slow to disappear after the vegetation is removed (Callaway *et al*. 1991, Schlesinger *et al*. 1996). In a study on the localised effects of *Acacia papyrocarpa* on soils and vegetation of open woodlands of South Australia, Facelli and Brock (2000) documented strong heterogeneity of resources produced by these trees, and suggested that this could be a major controlling factor in the productivity of the system. After the death of the trees there was no residual accumulation of nitrogen after 40 years, but there was some retention of phosphorus and organic matter. However, it is important to note that the system studied had little topographic relief, and therefore material transport was expected to be slow. With an inevitable redistribution of nutrients over time after the vegetation has been removed, a more homogeneous landscape would develop and would consequently produce a less productive ecosystem (Noy-Meir 1981) and possibly a less diverse one. Hydrological processes which result in greater water storage under vegetation are related to the accumulation of nutrients and this effect will be negated once the vegetation is cleared. On slopes when the vegetation is cleared there is an increase in erosion and the water dynamics are changed (Ludwig *et al*. 2005) (Chapter 3). The clearing of vegetation, especially in terrain with dunes, can result in changes in the productivity of the ecosystem due to the redistribution of nitrogen, phosphorus, potassium, and organic matter. The pH and conductivity can be changed or remain unchanged by disturbance. Each of those soil components have distinct dynamics and consequently may be changed at different rates (Facelli and Brock 2000).

The soils of the tracks studied here are fine textured in the swales and coarser along the slopes (Chapter 3). The finer particles with their elevated nitrogen and phosphate content are mobilised early in a rainfall event, and so their accumulation in the swale would be expected (Palis *et al*. 1997b). With the conversion of NH_4^+ to NO_3^-, which is water soluble, nitrogen can be redistributed through leaching, where it will move down through the soil profile, particularly in sandy soils, to below the root zone and into the ground water where it can be redistributed via underground run off. This occurs to a lesser extent with phosphate. However, as most of the soil nitrogen is associated with organic matter any changes to the soil profile produced by disturbance which affect the decomposition of organic matter would also affect the available nitrogen. Another possible effect on nitrogen is through an increase in mineralization due to higher temperatures, which could be a factor where there is no vegetation. However, soluble fractions are a small proportion of the total, and so erosive processes have a greater affect and that is how the bulk of the minerals are transported. If the soil becomes waterlogged, as could be possible in the swales of dunal country, nitrogen can also be removed from the system by denitrification. Potassium can only be accessed by plants in the water soluble form and when associated with clay particles, and so its distribution is also prone to changes in soil and water movement. With the redistribution of nutrients and soil water there is the likelihood of pH changes in areas of disturbance (Migge-Kleian *et al*. 2007).

Vegetation clearance increases the chance of a rise in soil electrical conductivity (EC) (Allison *et al*. 1990). This can be an indication of the amount of dissolved nutrients in the soil water, and so the higher the better for plant growth. However, as conductivity increases above a certain level plant growth can be compromised. The relationship between water dynamics and EC was shown in a study in Canada by Kachanoski *et al*. (1988) who found a linear relationship between soil moisture and EC in soils with up to 25% volumetric water content, but above this there was no change. Kitchen *et al*. (2005) showed that in high rainfall areas EC was correlated with bulk density, clay, silt and sand content, CEC (cation exchange capacity), elevation and slope, while total carbon, nitrogen and soil microbial properties were not correlated.

Johnson *et al*. (2001) showed that the variables of bulk density, clay, and pH were positively correlated with EC over a soil depth of 0 – 30 cm, while soil water, total carbon and nitrogen were negatively correlated. They suggested that in agricultural systems EC may be a consistent predictor of yield potential across years in environments where rainfall is the main limitation to crop yield. Balkom *et al*. (2005) also found elevation, slope, and EC readings to be distinguishable between landscape positions with the EC reading correlating to soil texture, and high positive values corresponding to high clay content (Shaw and Mask 2003). These studies show varying correlations between the physical and chemical characteristics of the soil and the EC and pH indicating that there are complex interactions.

The removal of vegetation is likely to change the litter content on the soil surface and the root content underground. The presence of litter influences the physical and chemical environment by decomposing and releasing nutrients into the soil, intercepting light and reducing evaporation (Facelli and Pickett 1991b, Facelli and Pickett 1991c). This has possible consequences for the succession of vegetation after clearance. Soil organic carbon is an essential factor in microbial mediated processes such as nitrogen cycling (Bennett and Adams 1999). It is important in binding soil particles together (aggregation) (Rillig and Mummey 2006), and can significantly influence soil water holding capacity, especially in sandy soils. The question can be raised then, of whether there was a likelihood of less carbon available in the soil of the disturbed area to provide nutrition for below ground biota and as nutrition for potential plant growth, or, are the dynamics such that there would be little change where clearance has taken place.

The creation of tracks for mineral exploration in this system with dunes can have multiple effects on physical processes that control the availability of water and nutrients. The topographic characters of the system may also contribute to the changes in patterns, since the intensity of the various processes will vary with topographic position.

This chapter aims to answer the following questions:

- Were the chemical characteristics of nutrient concentrations, pH, conductivity and carbon litter in the soil different in the disturbed and undisturbed areas with respect to the topographical features of the study site?
- Did the different physical characteristics of the system in the disturbed area influence the chemical characteristics and if so how?

Methods

The data sets were collected from three tracks at four positions across the tracks; centre, wheel rut, shoulder and undisturbed (microtopography) from four positions along the tracks; swale, footslope, slope and crest (topography) as shown in Chapter 3 (Figure 3.2). Details of the location of tracks and how they were created are given in Chapter 2.

4.1 Total Nitrogen, Phosphorus and Potassium

Soil samples were collected using a 10 cm diameter cylinder pushed to a depth of 10 cm from the three tracks at four positions across the tracks from four positions along the tracks, without replication. These 48 samples were collected in October in spring, stored at 5^0C until July of the next year and were then sent to the CSBP Soil and Plant Analysis Service in Western Australia for analysis for total nitrogen (%), available phosphorous (mg/kg) and potassium (mg/kg) (Colwell P + K).

4.2 pH, Conductivity

Subsamples weighing 5 g from each of the samples collected for the nutrient analysis were mixed with 50 ml of water, centrifuged for 30 mins and allowed to settle before the pH was measured using a pH-meter (Cyberscan, USA) and the conductivity was determined by Water and Soil Salinity Monitoring Kit (NSW DPI, Wagga Wagga) using $EC_{1:5}$ method in the laboratory.

4.3 Litter

In September 2005 (spring) the amounts of standing litter, which consisted mainly of small sticks, bark and some leaf material from eucalypts, *Callitris* sp. and *Melaleuca uncinata* and some kangaroo droppings, were assessed. The percent cover was recorded in 20 cm x 20 cm quadrats at each position along the three tracks at the swale, footslope, slope and crest. Quadrats were placed at five randomly appointed points within a five metre section at the centre, wheel rut, shoulder and the undisturbed area (five metres from the edge) giving 240 samples in total.

4.4 Total Carbon

The total carbon content of the same soil samples used for estimating the pH was determined using Walkley and Black rapid titration procedure (Walkley and Black 1934). Soil was taken from 5 cm deep samples collected from each of the tracks at the swale, slope and crest from the centre, wheel rut, shoulder and undisturbed area resulting in 36 samples. The footslope was omitted to reduce the number of samples to be analysed, as the available facilities and equipment were limited. One gram from each sample was thoroughly mixed and sieved through a 0.5 mm sieve.

Statistical Analyses

The data sets were analysed with the appropriate statistical test for the analyses of variances performed and the role of the dispersion of replicates determined as in Chapter 3.

Total nitrogen, potassium, pH and conductivity

Total nitrogen data set was arcsine transformed and then analysed. All the other data sets other than total carbon were not normal and data transformations could not rectify this. Permutation based nonparametric multivariate analysis of variance (PerMANOVA, (Anderson 2005) was therefore performed (as described in Chapter 3) to assess the differences in total nitrogen, potassium, pH and conductivity between the positions across the tracks and between the positions along the tracks. The three tracks were used as replicates, since there was only one sample taken from each position.

Litter

This permutational multivariate analysis of variance was used to assess the differences in litter accumulation between positions across the tracks when they were nested within positions along the tracks and tracks, as well as differences between positions along the tracks when they were nested within tracks and between tracks using five replicates.

Total carbon

The total carbon data set was arcsine transformed and analyzed using a two-way ANOVA conducted with Bonferroni post tests.

For positions across the tracks the variances were homogeneous for total nitrogen, potassium, pH and total carbon and heterogeneous for conductivity and litter. For the positions along the tracks the variances were homogeneous for pH, litter and total carbon and heterogeneous for total nitrogen, potassium and conductivity.

In the case of phosphorus no statistical analysis was possible as the levels detected were so low that the results were only just detectable within the parameters used by the CSBP Soil and Plant Analysis Service soil analysis.

Results

4.1 Total Nitrogen, Phosphorus and Potassium

Total Nitrogen

There were no significant differences in total nitrogen across the tracks (Figure 4.1a)). There were differences along the tracks, with the swale having significantly more nitrogen than the slope PerMANOVA (t=2.49, p<0.0.025) (Figure 4.1b)). There were no interactions between the positions across and along the tracks.

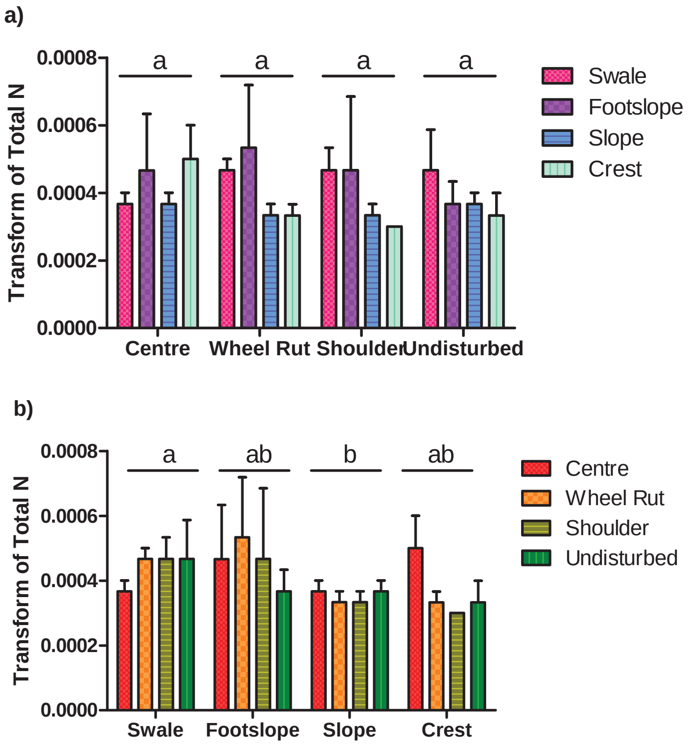

Figure 4.1 Percent of total nitrogen in soil samples a) across and b) along the tracks (±95% CI, n = 3) - letters denote differences at ($p<0.05$) level

Phosphorus

The score for phosphorous content was 2 mg/kg for all positions along and across the tracks except for Track 1, where the footslope at the centre and shoulder each had 3 mg/kg.

Potassium

There were no significant differences in potassium across the tracks (Figure 4.2a)). There were differences along the tracks, with the swale having more potassium than the slope PerMANOVA ($t=2.79$, $p<0.025$) (Figure 4.2b)). There were no interactions between the positions across and along the tracks.

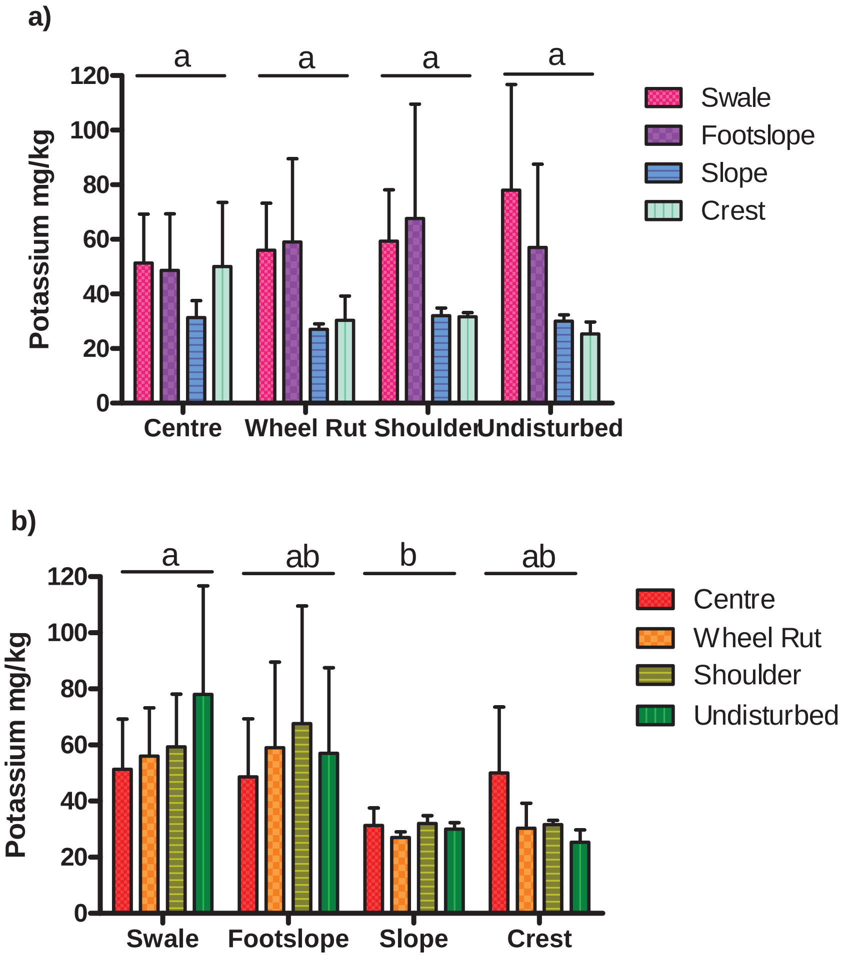

Figure 4.2 Potassium content a) across and b) along the tracks (±95% CI, n = 3) - letters denote differences using at ($p<0.05$) level

4.2 pH, Conductivity

There were significant differences across the tracks with the pairwise comparisons showing that the wheel rut had a higher pH than the shoulder (PerMANOVA $t=2.91$, $p<0.025$) (Figure 4.3a)). There were no significant differences in the pH along the tracks (Figure 4.3b)) and there were no interactions between the positions across and along the tracks.

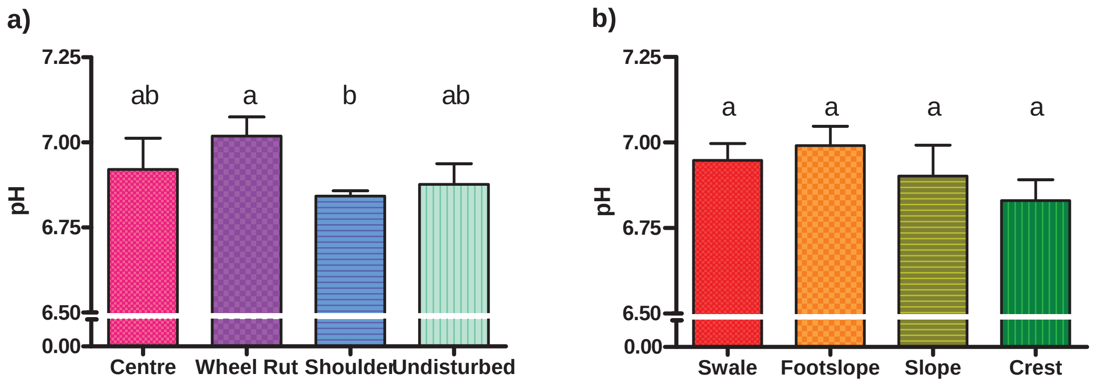

Figure 4.3 Soil pH a) across and b) along the tracks (±95% CI, n = 3) - letters denote differences at ($p<0.05$) level

There were no significant differences in conductivity between positions across (Figure 4.4a)) the tracks or between positions along the tracks (Figure 4.4b)) and there were no interactions between the positions across and along the tracks.

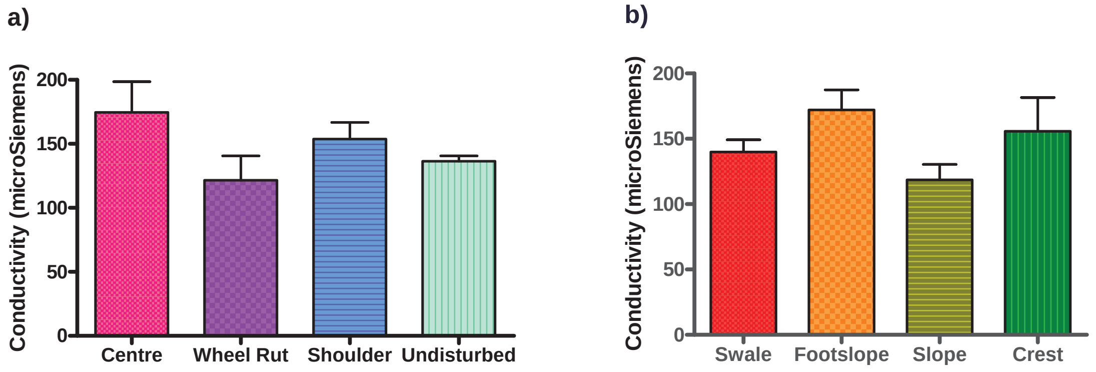

Figure 4.4 Conductivity a) across and b) along the tracks – no significant differences (±95% CI, n = 3)

4.3 Litter

There were differences between positions across the tracks when nested within tracks and positions along the tracks (PERMANOVA version 1.6 $F_{36,239}=4.84$, $p<0.001$). The undisturbed position had more litter than the centre ($t=4.55$, $p<0.01$), wheel rut ($t=4.58$, $p<0.01$) and shoulder ($t=4.04$, $p<0.01$) at the footslope in Track 1 and more than the centre ($t=7.3$, $p<0.001$), wheel rut ($t=7.62$, $p<0.001$) and shoulder ($t=7.23$, $p<0.01$) at the slope in Track 2. The shoulder had more litter than the centre ($t=3.87$, $p<0.01$) and wheel rut ($t=4.14$, $p<0.01$) at the slope in Track 3 (Figure 4.5a)).

There were no differences between positions along tracks when nested within tracks (Figure 4.5b)).

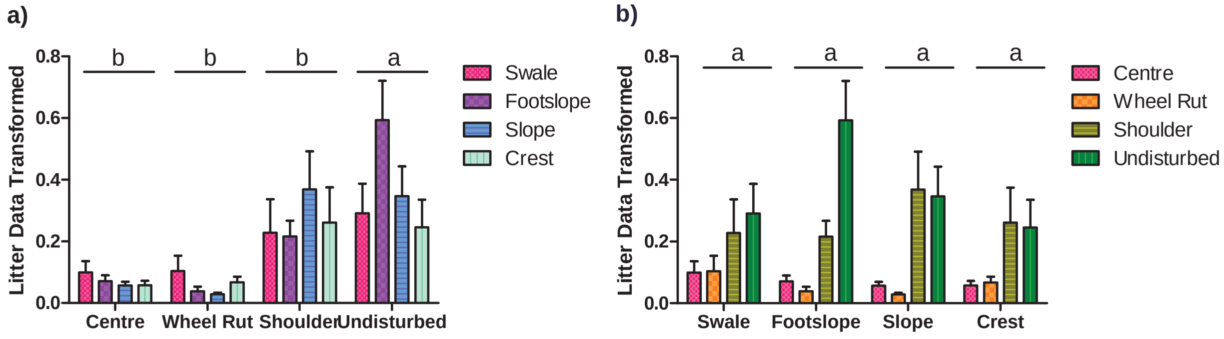

Figure 4.5 Percent litter cover a) across and b) along the tracks (±95% CI, n = 20) - letters denote differences at (p<0.05) level

Results from PERMDISP for the permutational tests of multivariate dispersion of replicates among tracks and among across when nested within tracks.

There were no differences in between tracks, but there were differences between positions across tracks when they were nested within tracks, based on the dispersion of replicates, ($F_{9,59}$=8.81, p<0.001). The pair-wise tests showed the centre as greater than the wheel rut in Track 1 (t=2.07, p<0.01), the shoulder greater than the centre (t=2.9, p<0.025) and wheel rut (t=3.16, p<0.01) and the undisturbed greater than the shoulder (t=2.8, p<0.025) in Track 3. Furthermore the undisturbed area was greater than the centre (t=4.51, p<0.01), wheel rut (t=4.55, p<0.05) and shoulder (t=3.95, p<0.025) in Track 2.

Thus, the differences between litter cover at the across positions could be due to the actual differences or due to the heterogeneity of variances or a combination of both.

4.4 Total Carbon

There were no significant differences for the total carbon content of the soil between the positions across (Figure 4.6a)) or along the tracks (Figure 4.6b)) and there were no interactions between the positions across and along the tracks.

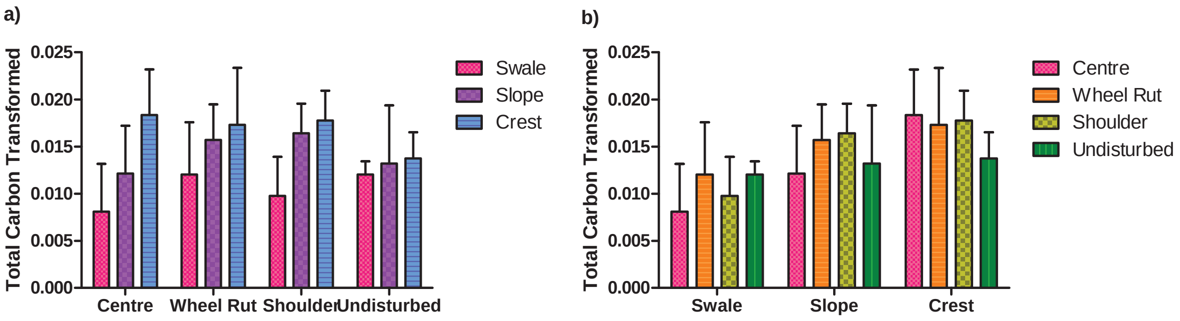

Figure 4.6 Total carbon a) across and b) along the tracks – no significant differences (±95%, n = 3)

Discussion

This study documented a complex pattern of heterogeneity in the variables measured and found that some were affected by topography, and some by the disturbance (Figure 4.7). In addition, there was small scale variation produced by the microtopography induced by the creation of the tracks.

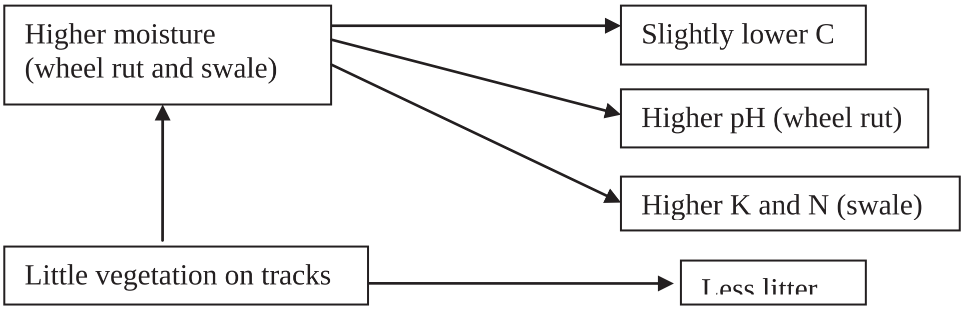

Figure 4.7 Summary of spatial heterogeneity in nutrient distribution

Apart from the distribution of litter, the characteristics of nitrogen, phosphorus, carbon and conductivity were seemingly less affected by vegetation clearance than were the physical properties of the system, such as compaction, bulk density, soil water content and erosion, which were notably altered, as described in Chapter 3. Chemical changes have been shown in this study to change along with some of the physical conditions. Due to these possible connections these changes in soil chemistry could be exacerbated over time in the disturbed area due to erosion and changes in water dynamics from the clearance of vegetation and subsequent compaction of the soil. There are problems associated with correlation studies as there can be difficulties in interpretation due to the many interacting variables involved (Sollins 1998). However, the results indicate possible connections, which can be followed up with more in depth research.

The soil texture consisted of smaller particle sizes in the swale (Chapter 3) than the slope and crest, and finer soils tend to have more nitrogen than coarser soils (Palis *et al*. 1997b). Total nitrogen loss in the soils from slopes can increase as the amount of erosion increases (Palis *et al*. 1997b). The results in this study suggest an accumulation of nutrients in the swale, which follows the source sink model (Ludwig and Marsden 1995). Since the swale area is a small component of the landscape compared to the other sections along the tracks a much higher concentration would be expected (Ludwig and Marsden 1995). This is potentially important if the concentration of the rich patches is well above the saturation of the response of the plants (and for these plants this is probably quite low), then productivity can decrease (Facelli *pers comm*. 2010). The swale is also the area with the most compaction, which is a soil characteristic that can limit plant growth. This accumulation of nutrients may not result in an increase in productivity, on the contrary it could lead to a reduction. The depletion of nutrients along the slope would also possibly hinder the regrowth of vegetation (Ludwig *et al.* 2005). Ludwig and Tongway's (1995) study in *Acacia aneura* (mulga) woodlands in eastern Australia found greater differences between positions within stands of trees compared to between stands in the available nitrogen and soil organic carbon in the top 10 cm layer of soil. This indicated this to be the layer to reflect the movement and accumulation of nutrients (Ludwig and Tongway 1995). Bainbridge (1999) found phosphorus and nitrogen levels tend to be concentrated in the top 2-3 cm of soil in dry land soils, which would be even more vulnerable to soil and water movement.

In their study of heath vegetation communities in a sandy heath environment in Ngarkat CP in South Australia Pelton and Conran (2002) found that there was a trend towards higher nitrogen in an undisturbed area compared to tracks. The results of the present study may substantiate the suggestion of Schlesinger *et al*. (1996) that patches of high nutrient concentrations under vegetation are slow to disappear after the vegetation has been cleared. A long term study would be necessary to confirm this. It is important to note that measurements reported herein were taken prior to erosion events that led to soil movement in 2007 (Chapter 3). If the soil samples had been collected after this event the results may have reflected those of Palis *et al.* (1997a), where the movement of finer particles down the slope resulted in the concentration of the smaller size soil particles increasing with time in the eroded sediment resulting in an increase in total nitrogen and organic carbon relative to the original soil. The potassium content of the soil analysed here showed a similar pattern to the nitrogen with the swale having significantly more than the slope. This is potentially important since potassium is associated with the inorganic component of the soil.

High chroma red and yellow colours (hues) indicate less oxidising conditions, and this was the hue of the soil at the crest and in the undisturbed area (Chapter 3). The swale showed lower chrome red and yellow colour indicating a more oxidising environment than at the crest. Thus it might be expected that the pH would be lower in this position, however this was not the case. The pH was significantly higher in the wheel rut than the shoulder, but was still within the range for optimal plant growth (Peverill *et al*. 1999). The wheel rut was more compact and held more moisture than the shoulder and these physical features indicated important consequences of disturbance (Chapter 3). This supports the findings of Pelton and Conran (2002) related to tracks that were created by cross-ribbed rolling, a technique routinely used to construct firebreaks along the margins and access tracks of Ngarkat Conservation Park, South Australia. Pelton and Conran (2002) found that the pH was significantly higher in rolled areas than in unrolled areas. This micro topographic effect could change the availability of the strongly pH dependent micronutrients of zinc and molybdenum (Peverill *et al*. 1999). Pelton and Conran (2002) suggested the higher pH observed in the disturbed area was due to lower organic content of the soil, however there were no differences in organic content found the present study. There were no differences found in my study in EC, which was not expected as there were differences found in clay and soil moisture between positions and large differences in compaction. These characteristics normally influence EC (Doerge 2001). These results could be clarified in future studies using greater replication.

Litter levels found in the present study were, as expected, lower on the tracks than in the undisturbed area. This was particularly evident in the centre and wheel rut, and the shoulder position was in between the two extremes. There had been no recent use of the tracks by vehicles, and so it would be expected that there would be some accumulation of litter in the wheel ruts. This was not the case, though, as the litter accumulated mostly in the positions where there was vegetation still growing i.e. the undisturbed area. There were no significant differences along the tracks, which was rather unexpected, as there was the likelihood of movement of material down the tracks or possibly the removal of material by wind at the crest.

The total carbon content of the soil did not reflect the litter distribution as there were no significant differences detected at any position. This was not the case in a study by Pelton and Conran (2002) where soil carbon was higher in the undisturbed areas than in the disturbed areas, as was the case with the litter cover. This indicated that in the environment of the present study the presence of litter may not contribute very much to the nutrient composition, or the pattern of litter accumulation is too recent to have produced an effect on nutrient accumulation. Possibly, and given enough time, the decomposition of organic matter would add more carbon to the soil. There is also the possibility that the withdrawal of nutrients from leaves, shoots, bracts etc prior to their senescence could be a factor, as Pate and Dell (1984) observed in their study of fire ephemerals in south-western Australia. This would, however, also occur in the sandy heath vegetation communities in Pelton and Conran's (2002) study. Further studies are needed on the decomposition characteristics of different vegetation types, particularly in areas with sclerophyllous vegetation and low nutrient soils.

Soil water is one of the most important factors in the production and decomposition of vegetation (Weaver *et al*. 1987, Sanford *et al*. 1991, Silver *et al*. 1999, Wang *et al*. 2002). Decomposition can be restricted by high water content in mineral soils resulting in less respiration by soil organisms as there is less available oxygen (Silver *et al*. 1999). This was not the situation in this study, which has shown that the percentage of soil water at all positions was very low. However, it must be noted that temperatures that are too high can restrict decomposition (Lal 2006), which is pertinent to this study where soil temperatures would likely to have been quite high due to the proportional relationship between air and soil temperatures (Watson 1980). Where the vegetation has been cleared the temperatures would be expected to be higher. There is little information on these soil temperatures in semi-arid Australia. It would be of interest to study the soil temperature over time along with the carbon content of the soil. Overall, the low carbon levels were typical of the arid and semi-arid landscapes in Australia, which consist of extremely low organic matter. This is often less than 1% (Bennett and Adams 1999) and 75% of Australia exhibits this characteristic (Chartres 1992). Rainfall and subsequent plant productivity is also extremely variable both within and among years, with annual periods (and sometimes years) of prolonged drought all affecting plant decomposition.

From the research presented here it is apparent that there were a several complex interrelationships at play between the chemical characteristics and these were affected by both the physical and the biotic environment. While this is a limited study, it suggests that the physical features of soil texture, topography, compaction, soil water and the amount of soil movement all have a role in determining the chemical nature of the environment, in both the disturbed and undisturbed areas. The results show that topography plays a large role in determining any differences in the soil chemistry, with few differences between the disturbed and the undisturbed areas. There could be a different scenario as more heavy rainfall events occur over time and subsequent erosion on the tracks takes place.

To conclude, the physical changes as assessed in Chapter 3 seem to be stronger than the chemical ones. The composition and characteristics of the above and below ground vegetation affect the chemical and physical features while at the same time there is a feedback mechanism of their growth being determined by these abiotic features. To distinguish the relative role each factor plays on the growth and composition of plants more directed research on the pertinent species would give valuable information to assess the relationships impacted on by the linear disturbance.

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Chapter 5 Emergence studies on the soil seedbank in disturbed and undisturbed areas

Introduction

The soil seedbank composition is a major determinant of vegetation dynamics, as many species recruit from the soil seedbank rather than from newly released seeds. This stage of a plant's lifecycle is extremely important as some species spend the majority of their life in seed form before emergence (Wardle 2003). Even though the dominating species of mallee eucalypts and *Melaleuca uncinata* are resprouters, the recruitment strategy of many species is via the soil seedbank (Grimes 1981). Once vegetation is cleared plant succession processes will determine the composition of the community at any one time (Connell and Slatyer 1977). The relationship between the soil seedbank and successional dynamics is complex (Jimenez and Armesto 1992).

The physical, chemical and biological characteristics of the upper soil layers changed by disturbance influence the soil seedbank characteristics (DeFalco *et al*. 2009). Little is known about the effects of environmental characteristics changed by disturbance on the soil seedbank, as few studies have been conducted on these conditions while assessing the soil seedbank (DeFalco *et al*. 2009). The information gained on the properties of the soil near the surface and the seedbank can aid in determining the degree of impact of the disturbance and the potential for regeneration and possible management strategies (DeFalco *et al*. 2009).

There is little known in relation to seedbank characteristics in relation to topography, let alone in relation to the combined effects with linear disturbance. A study in southern New England in USA found more species and germinants in the valleys with a progressive decline from the midslope to the ridge top (Ashton *et al*. 1998). However, this study was conducted without taking any disturbance regime into account, and was located in a moist deciduous forest, which is a different environment to a semi-arid mallee system. There have been few studies on the role of the soil seedbank in recruitment after disturbance in such systems. Arid and semi-arid lands are vulnerable to desertification due to surface disturbances affecting the presence of viable seeds in the uppermost layers of soil (Aranda and Oyonarte 2005). As different species have varying regeneration strategies, the question arises as to which species are the most successful in regeneration, and what are the characteristics of these species. The seed characteristics and abundance in the top soil can provide valuable information to determine the severity of a disturbance and the potential for vegetation establishment and recovery (DeFalco *et al*. 2009).

The establishment of vegetation and the subsequent growth of particular species are reliant on the characteristics of the first species regenerating after disturbance. These species may, or may not, provide a beneficial environment for the growth of subsequent species (Connell and Slatyer 1977). For example, the subsequent vegetation can grow even though resources have been depleted by the initial population, or alternatively, species can only regenerate by being reintroduced into the disturbed area from external sources and when the conditions are more favourable for their growth (Connell and Slatyer 1977). Disturbances can change environmental conditions, such as compaction, water infiltration, nutrient availability and biota composition. This creates several problems to be overcome for seeds to germinate, seedlings to survive and grow, and for plants to reproduce. As Noble and Slatyer (1980) stated, the observed pattern of succession is "an inevitable consequence of the relative availability of a range of species and their life history characteristics."

The composition of the plant community, affected or not by disturbance, is reliant on which reproductive propagules are present to initiate growth. This is determined by the local vegetation, the manner in which their seeds are dispersed, the environmental factors which affect this dispersal and seed storage. In southern Australia more than one third of species have their seeds dispersed by ants (Berg 1975). Ants also play a role in determining the seedbank dynamics by consuming seeds, e.g. they are the dominant consumers of eucalypt seeds after the seeds fall to the ground. This harvesting of seeds can limit regeneration, particularly when harvester ants are present, and they can remove 60 – 100% of seeds (Anderson 1982, Wellington and Noble 1985). Fire also plays an important role in dispersal through enabling the release of seeds stored in the canopy of serotinous species. Hence, the manner in which seeds are dispersed can provide valuable information on the potential regeneration process in disturbed areas (Bradstock *et al.* 1996).

Fire affects germination through the breaking of the seed coat by heat and through the stimulatory effect of the products of smoke and ash. Australian plants have much higher germination rates using a stimulus of a smoke cue than without, in some of the experiments conducted to encourage germination (Dixon *et al*. 1995). As fire is an important factor in the successful germination of many species, it is important to identify the species that require fire to determine those that are more likely to regenerate in the absence of fire. Some species are more likely to grow from the seedbank than others after disturbance.

There is the possible effect of further disturbance occurring in addition to the original disturbance. As fire is an important factor in the regeneration of a number of Australian species it would be expected that in disturbed areas the occurrence of fires would influence succession. Many plants able to regenerate vegetatively from underground structures, such as lignotubers, would be at an advantage after disturbance by vegetation clearance, or fire, as long as the lignotuber is not damaged (Noble 2001). This regeneration is vulnerable to the number of times clearance of the above ground coppicing from the lignotuber by either cutting or burning takes place (Noble 2001). Droughts are also an inherent part of the Australian climate and would have an effect on the successful germination and regrowth of the vegetation. Occasional heavy rainfall events are an added feature of the semi-arid zone and this can cause soil and litter movement. Water runoff may bury seeds just below the soil surface or quite deeply depending on the amount of movement. A layer of soil can provide insulation for buried seeds in high temperatures, however if it is thin this insulation capacity would be unlikely enough to reduce the temperature in a fire to levels where seeds are likely to survive (Hughes *et al*. 1994) .

The future vegetation composition may be affected if the existence of tracks changes the seedbank characteristics, the potential contributors to the seedbank from the existing vegetation and the conditions for seed dispersal. Any changes in the landscape functioning due to the physical and chemical environment created by this type of linear disturbance can affect these factors. These characteristics are, therefore, linked to the subsequent dynamics in vegetation germination, emergence and growth. The topography of the area would also have a possible influence on the growth and distribution of the plant community.

The aim of this chapter is to answer the following questions:

- What were the potential contributors to the seedbank from the vegetation populations?
- Were there differences in the distribution and composition of seedlings emerging from the soil seedbank along the topographic gradient, and were any patterns similar between the disturbed and the undisturbed areas?
- How was the dispersal of perennial species, with particular reference to the role of ants, affected by the disturbance, and was there a topographical affect?

Methods

The data sets were collected from three tracks at four positions across the tracks; centre, wheel rut, shoulder and undisturbed (microtopography) from four positions along the tracks; swale, footslope, slope and crest (topography) as shown in Chapter 3 (Figure 3.2). Details of the location of tracks and how they were created are given in Chapter 2.

5.1 Emergence from the soil seedbank

The study of the seedbank has presented researchers with difficulties and there has been much debate on which is the best method (Espeland *et al*. 2010). Two methods often used are; that of extracting and identifying seeds, ‘extraction method’, and that of germinating the seedbank and counting and identifying emerged seedlings, ‘emergence method’. The first method, which can involve sieving, washing and flotation techniques and air classification, can accurately assess the composition of the seedbank (Mesgaran *et al*. 2007). However, this may not necessarily reflect the contribution to seedling recruitment in the field (Espeland *et al*. 2010). It is also time consuming and has funding and personnel issues (Espeland *et al*. 2010). The problems are exacerbated with extremely small sized seed, as is the case for many mallee species, and there are also difficulties in determining the viability of seeds (Gross 1990). The ‘emergence method’ is simple and often used instead of the first method (Clarke and Dorji 2008), but requires time for emergence to take place (Clarke and Dorji 2008). Also, there are temporal differences in the breaking of dormancy between species, which must be taken into account in planning experiments (Espeland *et al*. 2010). Espeland *et al*. (2010) showed lower emergence from two types of soil collected from the field than from germination experiments in Petri dishes. For this experiment two annual grass species (seeds collected from the field in Nevada) and four weedy forb species (seeds bought from an English seed firm) were used. This indicates that emergence studies possibly do not reflect the true abundance of germinable seeds in the soil. However, this lower level of emergence versus germination may indicate that this is an important limiting factor in plant recruitment in the field (Espeland *et al*. 2010). This is, therefore, an appropriate method to assess regeneration potential and is used in this study.

Soil seedbank 2006

Emergence from the soil seedbank was assessed by examining soil samples collected in April (autumn) in 2006 using a 10 cm diameter tube pushed into the soil to a depth of 5 cm at each position across and along the tracks, resulting in 144 samples. Samples were taken from the top 5 cm as it has been shown in previous studies that this section of top soil has the most seeds (Jimenez and Armesto 1992). The soil samples were placed in plastic containers (15 cm x 15 cm square) on top of a layer of sterile sandy soil in a glasshouse and watered regularly. After four months the species of seedlings that emerged were identified and the number of plants of each recorded. After a further two months the species were again identified and the number of plants of each recorded for the final reading. To aid with the identification, sample seedlings were transplanted to allow growth to flowering.

Soil seedbank with and without smoked water treatment 2007

To further examine the emergence from the soil seedbank using a smoked water treatment, two sets of soil samples were collected, using the same method as in 2006. This was done in April (autumn) in 2007 at the swale, slope and crest from each of the tracks at each of the four positions across the tracks resulting in 72 samples. The soil samples were placed on top of a layer of sterile sandy soil in plastic containers (15 cm x 15 cm square) in a glasshouse. Smoked water (Regen 2000 Smokemaster, Melbourne, Victoria) was applied to one set of the samples (36 samples). The smoked water was produced by burning predominately *Eucalyptus* spp. (but included some *Pinus* spp.) sawdust waste, and percolating the smoke through water (Wills and Read 2002). This was applied to one set of the soil samples (36 samples). This was applied once only in place of the first watering in a 50% dilution sprayed over the plastic containers resulting in 10 ml per container. There was no watering for the following week and then the samples were watered regularly after that. The other set of 36 soil samples were watered at the same times, but always with pure water. After four months the species of seedlings that emerged were identified and the number of plants of each recorded. After a further two months the species were again identified and the number of seedlings of each recorded for the final reading. To aid with the identification, sample seedlings were transplanted to allow growth to flowering.

5.2 Potential contributors to the soil seedbank

The mature perennial vegetation in the undisturbed area was surveyed using 10 m x 3 m quadrats 5 m from the edge of one side of the tracks in the undisturbed area at the swale, footslope, slope and crest resulting in 12 quadrats. The species were identified and the number of plants in each species counted. The perennial species were classified according to their dispersal strategies, which were determined from the literature and the characteristics of the morphology of the seeds (Hughes *et al.* 1994) (see Appendix 3). Seedpods and seeds were placed into six classes: unassisted, wind, vertebrate, fire dependent, ants and unknown.

The growth of annuals was assessed in September (spring) in 2005 using the percent cover and counting the number of species in four 20 cm x 20 cm quadrats, spaced so that there was one at each position across the tracks, i.e. centre, wheel rut, shoulder and in the undisturbed area with five replicates randomly placed within 5 m sections at the swale, footslope, slope and crest along the tracks, resulting in 240 scores overall.

5.3 Seed removal experiments

To determine the incidence of seed removal by ants seeds were placed into Plastic Petri dishes, 4 cm in diameter, which were glued on to the middle of 9 cm plastic Petri dishes, one of which was glued to the centre of each of 72 Masonite boards, 20 cm x 20 cm, for stability. Controls had Tanglefoot (Copyright © 1998-2002 The Tanglefoot Company) placed in the outer well of the larger Petri dish to prevent ants from removing seeds. Three seeds each of *Acacia rigens* A.Cunn. ex G.Don, *Eucalyptus incrassata* Labill., *Callitris verrucosa* (Cunn. ex Endl.) F. Muell. and *Leptospermum coriaceum* (F.Muell. ex Miq.) Cheel. were placed into these. A square wire cage with 1 cm^2 holes and about 8 cm high was placed over each board to prevent birds and mammals from eating the seeds. On each of the three tracks three replicates of the control and three of the treatment were placed in the disturbed and the undisturbed areas, at the swale and at the crest, resulting in 36 allowing access to the seeds and 36 not allowing access. The species from which seeds were used were chosen as they represented the largest proportion of the perennial vegetation in this area. In the morning and late afternoon the seeds taken were recorded and replaced.

Statistical Analyses

The data sets were analysed with the appropriate statistical test for the analyses of variances performed and the role of the dispersion of replicates determined as in Chapter 3.

Soil seedbank in 2006

For the 2006 data set on the emergence from the seedbank the number of seedlings and number of species were analysed to assess the differences between positions along the tracks, when they were nested within positions across the tracks and within tracks, and differences between positions across the tracks when they were nested within tracks and between tracks, using six replicates. To further test for an interaction between the positions along the tracks and those across the tracks the data was combined for the all the tracks and not nested. The data set was not normal for both the number of seedlings and the number of species and the variances for the number of seedlings were heterogeneous for the positions along the tracks and for the tracks, and for the number of species variances were heterogeneous for the positions for both across and along the tracks.

Soil seedbank in 2007 – smoked water treatment

For the 2007 data set on the emergence from the seedbank with and without the smoked water treatment the number of seedlings and number of species were analysed to assess the differences between positions across the tracks and between positions along the tracks using the three tracks as replicates. The tracks were used as replicates because replicate samples were not collected from each position. The data sets were not normal for both the number of seedlings and the number of species. For the data set for the control (no smoked water treatment) the variances for the number of seedlings were heterogeneous for the positions across the tracks. For the data set for the treatment the variances for both the number of seedlings and the number of species were homogeneous. There were no interactions for both the control and the treatment.

The number of seedlings emerging after the application of smoked water and non smoked water was compared between positions across the tracks when nested within positions along the tracks and within treatments, and between positions along the tracks when nested within treatments.

Perennial vegetation

The data set for the perennial vegetation was normal and the variances were homogeneous. A one way ANOVA was conducted and a Bonferroni post test. To analyse which species accounted for any differences between sections along the tracks in the undisturbed areas the data was corrected by deleting any species with fewer than three plants observed. An Indicator Species Analysis was conducted. This calculates the indicator value (fidelity and relative abundance) of species in clusters or types (Dufrene and Legendre 1997).

Annual vegetation

The data set for the annual vegetation was arcsine transformed and analysed to assess any differences in the cover of annual seedlings and the number of species of annual seedlings in the field. Analysis was between positions across the tracks when nested within positions along the tracks and within tracks, and between positions along the tracks when nested within tracks and between tracks, using five replicates. Both data sets were not normal and the variances were heterogeneous for positions across and along the tracks and for the tracks for percent cover and heterozygous for the positions along the tracks for the number of species.

Seed dispersal

The data set of the number of plants from the perennial vegetation in each category of seed dispersal strategy was normal and the variances were homogeneous. A one way ANOVA was conducted to assess for differences between the numbers of plants using the different dispersal strategies along with a Bonferroni post test. An Indicator Species Analysis was performed to analyse which dispersal strategies used by the plant species present in the undisturbed areas accounted for any differences between sections along the tracks.

Seed removal

The data set was analysed for differences in the number of seeds taken between the disturbed and undisturbed positions when nested within positions along the tracks and within tracks, and between positions along the tracks when nested within racks, and between tracks, using three replicates. The data set was normal and the variances were all homogeneous. Differences were tested between the number of acacia seeds and the number of eucalypt seeds taken by ants when nested within the disturbed and undisturbed positions, and within the positions along the tracks and within tracks, and the differences between the disturbed and undisturbed positions when nested within positions along the tracks, and within tracks and the differences between the positions along the tracks when nested within the tracks and between the tracks, using three replicates.

Results

5.1 Emergence from the soil seedbank

Soil seedbank 2006

In 2006 there were no overall significant differences in the number of seedlings or the number of species emerging from the soil seedbank between the disturbed and undisturbed areas. More seedlings emerged from the swale than from the crest (PERMANOVA version 1.6, $F_{12,143}=3.24$, $p<0.01$) in Track 1 in the wheel rut ($t=3.63$, $p<0.01$) and the shoulder ($t=2.49$, $p<0.05$), and in Track 2 in the centre ($t=2.79$, $p<0.05$), the wheel rut ($t=2.51$, $p<0.05$) and the shoulder ($t=1.69$, $p<0.05$). There were no differences between the swale and crest in the undisturbed area (Fig 5.1a)).

There were no overall significant differences in the number of species emerging from the soil seedbank between the disturbed and undisturbed areas. More species emerged from the swale than from the crest (PERMANOVA version 1.6, $F_{12,143}=3.13$, $p<0.01$) in Track 1 in the wheel rut ($t=3.39$, $p<0.01$) and Track 2 in the wheel rut ($t=5.07$, $p<0.05$) and shoulder ($t=2.18$, $p<0.05$). Again, there were no differences between the swale and crest in the undisturbed area (Figure 5.1b)).

There was not a significant interaction between the number of seedlings or between the number of species in the positions across the tracks and those along the tracks.

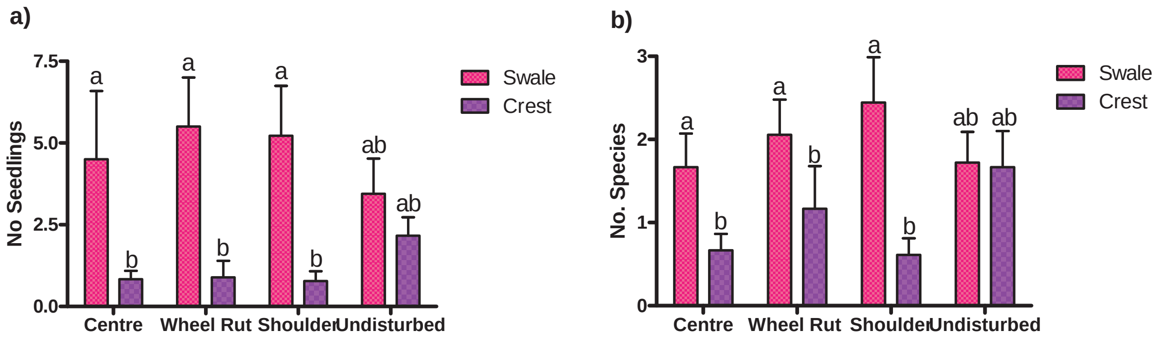

Figure 5.1 a) Seedlings and b) Species emerging from the soil seedbank from the positions along the tracks at the positions across the tracks from 2006 (±95% CI, n = 18) - letters denote differences at $p<0.05$ level

The difference observed in the number of species between the shoulder and undisturbed in the swale could have been also, or solely, due to the dispersion of replicates PermDisp ($F_{6,47,}$ $t=3.16$, $p<0.01$).

Soil seedbank in 2007 – smoked water treatment

From the samples collected in 2007 there were no significant differences in the number of seedlings emerging from the soil seedbank between the disturbed and undisturbed areas when not treated with smoked water. There was not a significant interaction between the number of seedlings or between the number of species in the positions across the tracks and those along the tracks.

There were more seedlings (PerMANOVA, $F_{1,23}=16$, $p<0.01$) (Figure 5.3a)) and more species (PerMANOVA, $F_{1,23}=20.5$, $p<0.001$) (Figure 5.3b)) emerging from the seedbank from the swale than the crest. There was a similar pattern to the 2006 data, although there were no significant differences in the undisturbed area between the swale and crest for both the number of seedlings (Figure 5.2a)) and the number of species (Figure 5.2b)). There was not a significant interaction between the number of seedlings or between the number of species in the positions across the tracks and those along the tracks.

The values for 2007 were much higher than those for 2006.

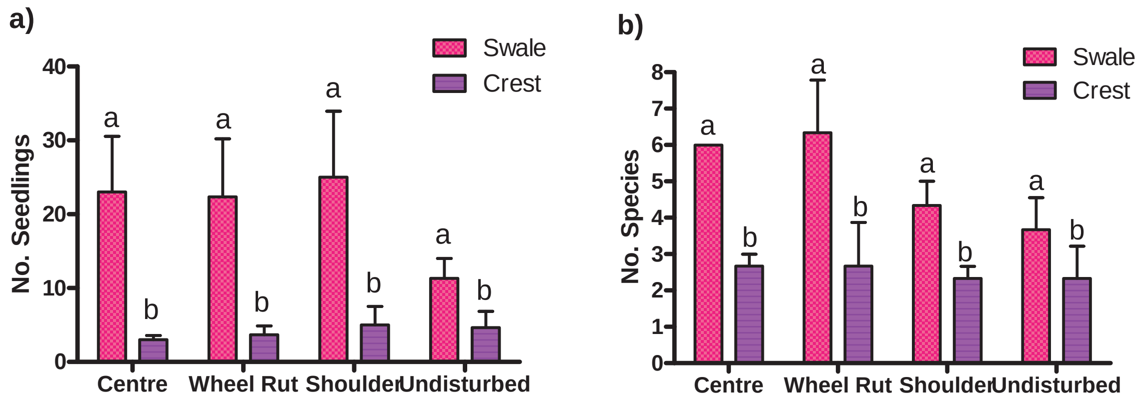

Figure 5.2 a) Seedlings and b) Species emerging from the soil seedbank from 2007 (±95% CI, n = 3) - letters denote differences at p<0.05 level

There were more seedlings (PerMANOVA, $F_{1,23}$=10.7, p<0.01) (Figure 5.3a)) and species (PerMANOVA, $F_{1,23}$=6.7, p<0.05) (Figure 5.3b)) emerging from the soil seedbank from the swale than the crest at the positions in the disturbed area, but not in the undisturbed area, when the smoked water treatment was applied (Figure 5.3). There was not a significant interaction between the number of seedlings or between the number of species in the positions across the tracks and those along the tracks.

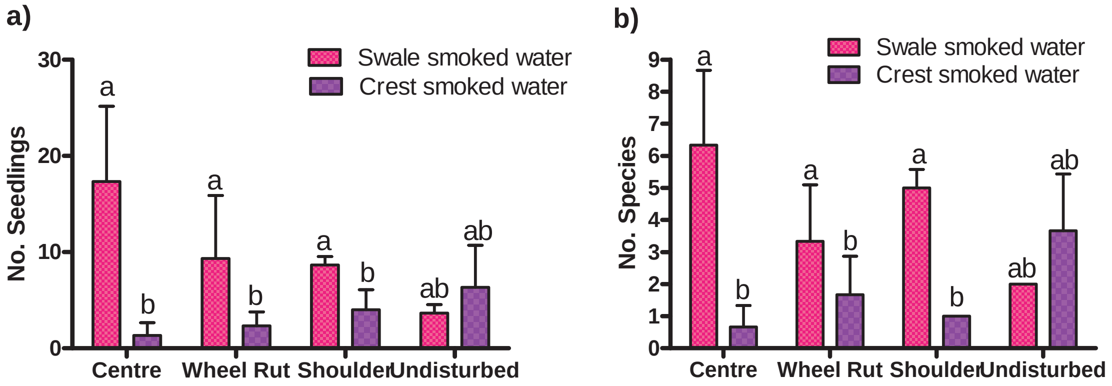

Figure 5.3 a) Seedlings and b) Species emerging from the soil seedbank from 2007 with smoked water treatment (±95% CI, n = 3) - letters denote differences at p<0.05 level

More seedlings emerged without smoked water than with the smoked water treatment (PERMANOVA version 1.6, $F_{1,47}=4.4$, $p=0.052$) (Figure 5.4a)). There were no significant differences between the disturbed and undisturbed areas. The swale had more seedlings emerging than the crest PERMANOVA version 1.6 ($F_{2,47}=11.99$, $p<0.01$), both with the smoked water treatment ($t=4.3$, $p<0.001$) and without smoked water ($t=2.14$, $p<0.05$) (Figure 5.4b)).

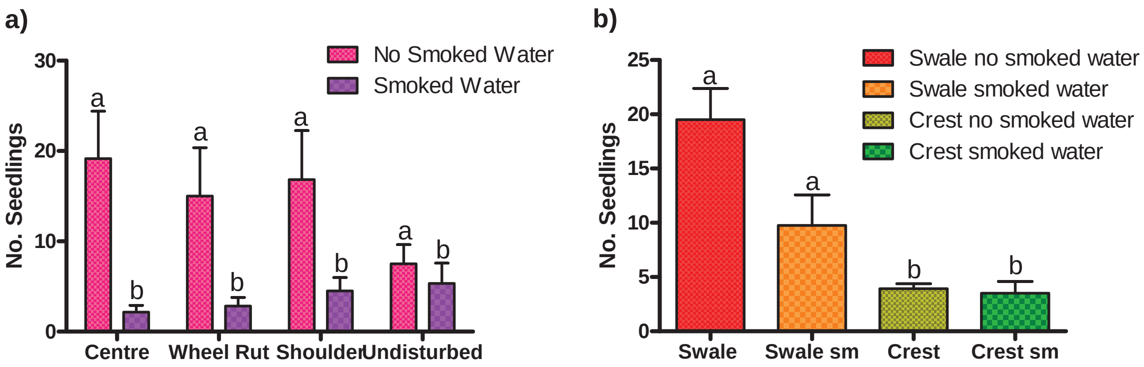

Figure 5.4 Seedlings emerging from the soil seedbank with and without smoked water treatment from 2007 from the positions a) across the tracks and b) along the tracks b), (±95% CI, n=3) - letters denote differences at p<0.05 level

Composition of the emergent seedbank

A total of 23 species emerged and were identified from the seedbanks of 2006 and 2007. There were no perennials identified in the emergent species. Most of the seedlings emerging consisted of the endemic annual species *Crassula colorata*. All the species identified were natives, except for *Hypochaeris glabra* (thistle) with one plant emerging (Table 5.1). Of the 23 species identified 10 emerged in 2006, 20 in 2007 without the smoked water treatment and 19 with the smoked water treatment (Table 5.1).

Table 5.1 Total number of seedlings emerging from all positions from 2006 (samples averaged) and 2007 with and without smoked water treatment

Plant species emerging from the soil seed bank	2006 ave.	2007 no smoked water	2007 smoked water
Actinobole uliginosum	0	5	4
Angianthus tomentosis	0	2	0
Brachycome sp	0.5	3	3
Calandrinia corrigioloides	3.5	34	15
Calandrinia eremaea	4.5	58	4

Calandrinia granulifera	2.5	12	2
Crassula colorata	17.5	91	53
Crassula sieberana	0	1	0
Helipterum demissum	0	1	1
Hypochaeris glabra	0.5	0	0
Isoetopsis graminifolia	3.2	28	3
Millotia tenuifolia var tenuifolia	0	10	11
Nicotiana sp	0	0	4
Podotheca angustifolia	0.2	2	5
Poranthera microphylla	1.2	13	22
Schoenus sp	0	1	3
Stenopetalum sphaeorcarpum	0	4	1
Trachymene cyanopetala	0	3	7
Triglochin calcitrapum	0	2	5
“daisy”	0	1	0
“grass”	3.8	6	1
“monocot”	0	0	4
“red stem”	0	0	1
unknown	31.7	8	14
TOTALS	**69.1**	**285**	**163**

In 2007 there were more seedlings emerging from the soil from the swale than from the crest and these consisted mainly of the species *Calandrinia eremaea*, *C. corrigioloides and Crassula colorata*, particularly in Track 1 (Table 5.2). There were more seedlings emerging with no smoked water from most positions along the tracks and with the four species (Table 5.2).

Table 5.2 The number of seedlings emerging from the soil seedbank in the smoked water and no smoked water treatments in 2007 samples using the four most commonly observed species emerging from the soil seedbank, Swale – red bold font, Crest – not bold

		Calandrinia	***Calandrinia***	***Calandrinia***	***Crassula***
		granulifera	***eremaea***	***corrigioloides***	***colorata***
Track 1	**No smoked water treatment**	**6**/4	**35**/4	**29**/1	**41**/2
Track 1	**With smoked water treatment**	**1**/0	**0**/2	**10**/2	**29**/10
Track 2	**No smoked water treatment**	**1**/1	**4**/1	**2**/2	**3/**0
Track 2	**With smoked water treatment**	**1**/0	**0**/0	**3**/0	**8**/0
Track 3	**No smoked water treatment**	**0**/0	**9**/5	**0**/0	**4**/8
Track 3	**With smoked water treatment**	**0**/0	**1**/1	**0**/0	**6**/0

5.2 Potential Contributors to the Seedbank

Perennial vegetation

There were 28 species identified in the above ground perennial vegetation. The main plants in the upper vegetation layer were *Callitris verrucosa*, while *Babingtonia behrii*, *Leptospermum coriaceum* and *Melaleuca uncinata* were the main plants in the mid layer and *Triodia* spp., *Dianella revoluta* and *Comesperma scoparium* were in the ground layer (see Appendix 3).

There were no significant differences between positions along the tracks in the one way ANOVA for the number of perennial plants in the undisturbed area (Figure 5.5).

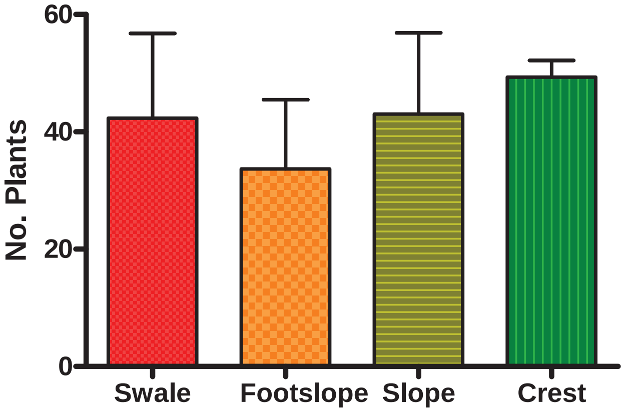

Figure 5.5 Perennial plants in the undisturbed area at positions along the tracks (swale, footslope, slope and crest) (±95% CI, n=3)

None of the species in the perennial vegetation in the undisturbed area explained significantly the differences between the sections along the tracks using Indicator Species Analysis (see Appendix 4).

Annual vegetation

There was greater cover of annual seedlings in the centre of the tracks than all the other positions across the tracks (PERMANOVA version 1.6, $F_{36,239}=4.3$, $p<0.001$) (Figure 5.6a) and Table 5.3). There was greater cover in the swale (PERMANOVA version 1.6, $F_{9,239}=2.3$, $p<0.01$) than in all the other positions along the tracks (Figure 5.6b)).

Table 5.3 The cover of annual plants where there was a significant difference at the positions across the tracks

Topographic position along the tracks	Position across the tracks	Pairwise test
Track 1 Swale	centre>wheel rut	(t=5, p<0.01)
	centre>shoulder	(t=4.7, p<0.01)
Track 1 Footslope	centre>undisturbed	(t=2.2, p<0.01)
Track 3 Swale	centre>wheel rut	(t=3.2, p<0.01)
	centre>shoulder	(t=3.2, p<0.01)
	centre>undisturbed	(t=3.6, p<0.01)
Track 3 Footslope	centre>undisturbed	(t=2.7, p<0.01)
Track 3 Crest	wheel rut>undisturbed	(t=2.5, p<0.01)

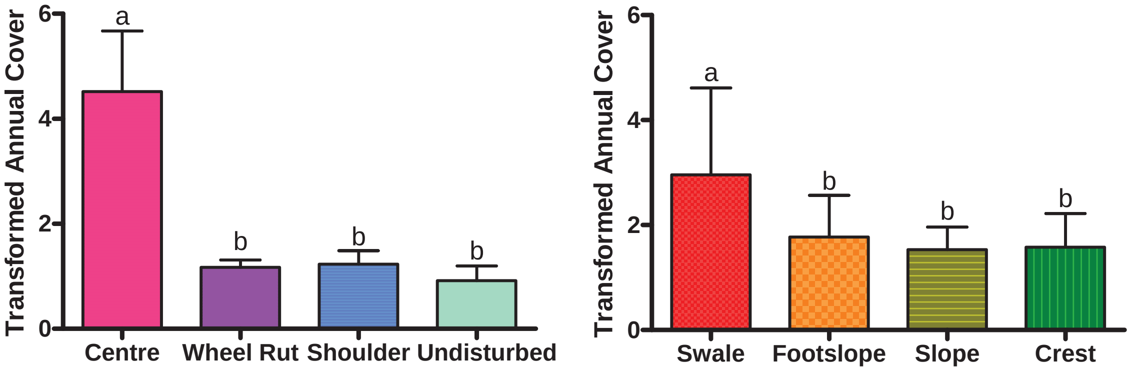

Figure 5.6 Annual plant cover a) across and b) along the tracks (±95% CI, n=15) - letters denote differences at p<0.05 level

There were more annual species in the centre than the other positions across the tracks (PERMANOVA version 1.6, $F_{36,239}$=2.7, p<0.001) (Figure 5.7a)) and in the swale than the other positions along the tracks (PERMANOVA version 1.6, $F_{9,239}$=11.3, p<0.001) (Figure 5.7b)).

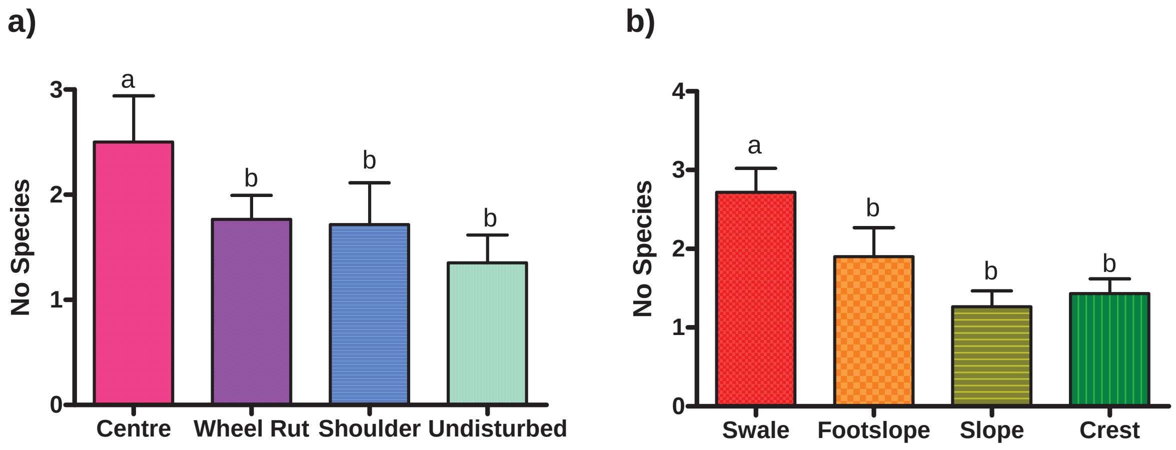

Figure 5.7 Annual plants – Species a) across and b) along the tracks (±95% CI, n=15) - letters denote differences at $p<0.05$ level

The footslope had more annual species than the slope in Track 1 ($t=3.1$, $p<0.0167$) and Track 2 ($t=5.9$, $p<0.0167$) and these differences could have been also, or solely, due to the dispersion of replicates.

Seed dispersal

There was a significant difference in the number of species with different dispersal strategies (one way ANOVA, $F_{7,64}=8.47$, $p<0.001$) (Table 5.4, Figure 5.9). There were more species that were myrmecochorous and/or predated upon by ants than the number of species using other strategies for their dispersal, particularly in the slope and crest (Table 5.4, Figure 5.8).

Table 5.4 No. of perennial species using the dispersal mechanisms of: unassisted, wind, vertebrate, fire dependent, ants and unknown, showing significant differences between these mechanisms at positions along the tracks

Comparison of dispersal mechanisms	**ANOVA**		
ants>fire slope	t=2.9, p<0.05		
ants>unassisted slope	t=3.4, p<0.01		
ants>vertebrate slope, crest	t=3.4, p<0.01, t=4.37, p<0.001		
ants>unknown slope, crest	t=3.4, p<0.01, t=3.9, p<0.001		
ants>wind/fire/ants slope, crest	t=3.4, p<0.01, t=3.9, p<0.001		
ants>wind footslope, slope, crest	t=2.9, p<0.05, t=4.37, p>0.001, t=2.91, p<0.05		
wind/fire>vertebrate crest	t=2.91, p<0.05		
wind/fire>wind crest	t=2.9, p<0.05		
fire>vertebrates crest	t=2.9, p<0.05		
fire>wind crest	t=2.9, p<0.05		

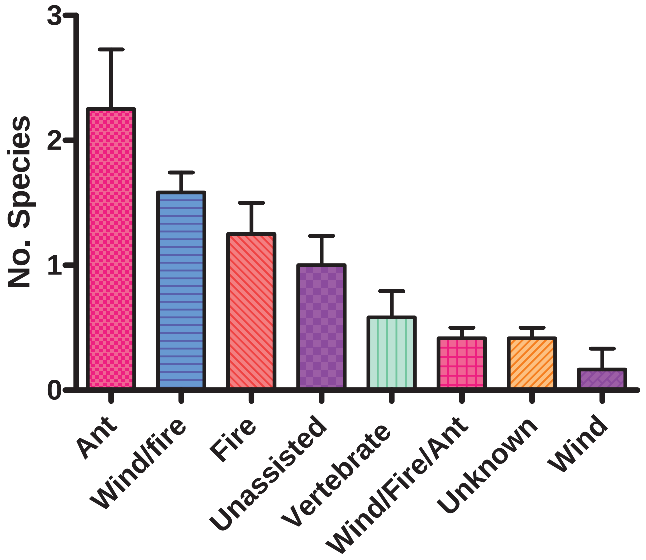

Figure 5.8 The dispersal strategies of perennial species in the undisturbed area

There were differences in the number of plants of species with different dispersal strategies with the highest numbers of plants being dispersed by wind/fire than the other strategies ($F_{7,64}$=4.8, $p<0.001$) (Table 5.5, Figure 5.9).

Table 5.5 No. of perennial plants using the dispersal mechanisms unassisted, wind, vertebrate, fire dependent, ants and unknown, showing significant differences between these mechanisms at positions along the tracks

Topographic position	**Comparison of dispersal mechanisms**	**ANOVA**
Crest	wind/fire>ants	t=3.1, p<0.05
Slope	wind/fire>unassisted	t=2.95, p<0.05
Crest	wind/fire>unassisted	t=2.8, p<0.05
Slope	wind/fire>vertebrates	t=2.8, p<0.05
Crest	wind/fire>vertebrates	t=3.9, p<0.001
Slope	wind/fire>unknown	t=3.4, p< 0.01
Crest	wind/fire>unknown	t=3.5, p<0.01
Slope	wind/fire>wind/fire/ant	t=3.2, p<0.01
Crest	wind/fire>wind/fire/ant	t=3.9, p<0.01
Slope	wind/fire>wind	t=3.4, p<0.01
Crest	wind/fire>wind	t=3.9, p<0.001
Swale	unassisted>wind/fire/ant	t=2.6, p<0.05

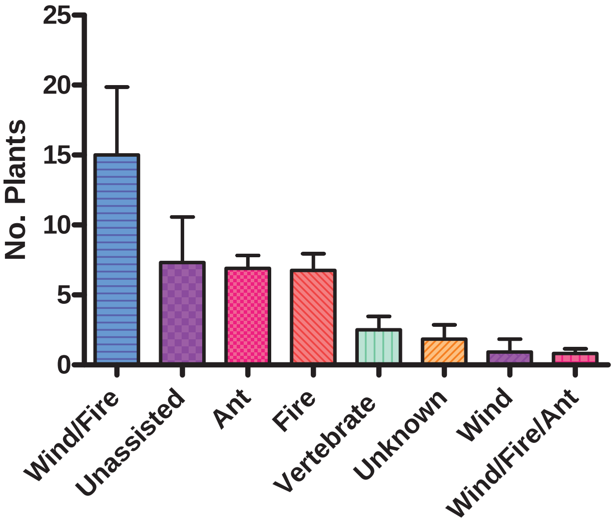

Figure 5.9 The dispersal strategies of perennial plants in the undisturbed area

While there were more ant dispersed species, those dispersed by wind/fire were more abundant.

None of the dispersal mechanisms explained the differences between the sections along the tracks using Indicator Species Analysis (Appendix 4).

The method of dispersal of *Callitris verrucosa*, which constitutes the main plant of the upper vegetation layer, consists of fire to open the cone and the winged seeds can then be dispersed by wind. However, the relatively high abundance of *C. verrucosa* suggests that there has been a long interval (>50 years) since the last fire as the abundance of this species has been shown to increase after such an interval (Bradstock and Cohn 2002). Apart from wind and fire, the next most common dispersal strategy was unassisted dispersal which was exhibited by *Babingtonia behrii*, the most common plant in the mid layer. *Leptospermum coriaceum* and *Melaleuca uncinata*, also in the mid layer, both benefit from fire to open the hard fruits and have very small seeds with no particular dispersal method. The latter also has lignotubers from which it can resprout. The dispersal of the most prolific species and main ground cover plants, *Triodia* spp., can be aided by fire and wind, and while they do not appear to be myrmecochores, they may still be eaten by ants (Westoby *et al*. 1988). The ground cover species, *Dianella revoluta* has fruit which are dispersed by birds, while the fruit of *Comesperma scoparium* are not fleshy and not attractive to birds, and so drop to the ground after drying out. Of the other perennials in this study the genera of *Lepidosperma*, *Hibbertia*, *Brachyloma*, *Leucopogon*, *Dillwynia*, *Acacia*, *Cryptandra* and *Boronia* are known to contain myrmecochorous species (Berg 1975). There were fewer plants of these genera growing in the field site than those with other dispersal methods.

5.3 Seed removal experiments

There were no significant differences in the number of seeds removed between the disturbed and undisturbed positions or positions along the tracks or between tracks from the PERMANOVA version 1.6 (Figures 5.10 and 5.11). The controls had no seed removal.

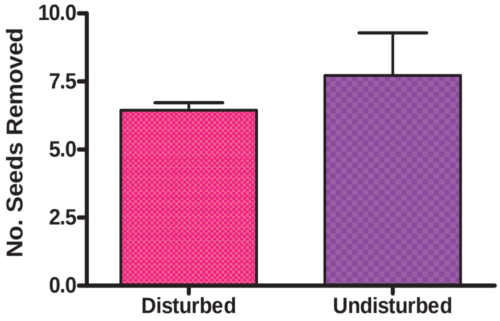

Figure 5.10 Seeds removed by ants in the disturbed and undisturbed areas (±95% CI, n=3)

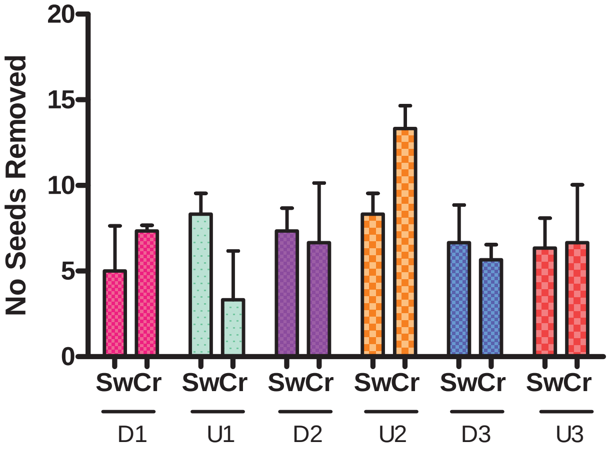

Figure 5.11 No. seeds removed by ants in the positions along the tracks in the disturbed and undisturbed areas of the three tracks (±95% CI, n=3)
Sw – swale, Cr – crest; D1, D2, D3 - disturbed Tracks 1, 2, 3; U1, U2, U3 – undisturbed Tracks 1, 2, 3

There were more acacia seeds taken than eucalypt seeds (PERMANOVA version 1.6, $F_{4,23}$=20.1, p<0.001) with no differences between the swale and the crest.

Only seeds of two of the four species (*Acacia rigens* and *Eucalyptus incrassata*) were taken by ants. In two instances seeds were not taken and the elaiosomes were missing, possibly indicating the removal of the elaiosomes by the ants on site.

Discussion

The main findings in this study of the emergence of seedlings from the soil seedbank have been that there was greater emergence from the swale than from the crest. This difference was greater in the disturbed area than in the undisturbed area and the seedlings emerging were all annuals. This effect of linear disturbance on the distribution of emergence was due to a number of environmental and biological characteristics changed in the disturbed area. Changes in soil characteristics and the clearance of vegetation were likely to be prime factors in determining the distribution of seeds in the soil seedbank. The lack of perennial vegetation on the tracks and the subsequent use of the tracks resulted in increased compaction and changes in the water and nutrient dynamics (Chapters 3 and 4). In the disturbed area there was also more erosion (Chapters 3) since slope, exposure and compaction changed transport processes across the landscape.

<u>The effect of erosion</u>

The pattern observed of more seedlings, at least from some species, emerging from the seedbank in the swale of the disturbed area than elsewhere, could possibly be due to seeds being carried down the slope with soil and water after heavy rainfall events (Reichman 1984, Garcia-Fayos and Cerda 1997). This secondary dispersal also influences the distribution of seeds through the soil profile. It plays a large role in determining the patterning of vegetation, which could more likely be reliant on the dispersal of seeds through the soil profile and laterally than on the initial movement of seeds from the plant to a surface (Chambers and MacMahon 1994, Emerson *et al.* 2010). The greater compaction in the disturbed area possibly increased soil and water movement (Chapter 3). The relationship between surface flows and related soil movement patterns and the distribution laterally of the soil seedbank is poorly documented (Garcia-Fayos and Cerda 1997, Jiao *et al*. 2009 and Emerson *et al.* 2010). The loss of biological crust, which stabilises the soil surface, and the sandy nature of the soil, would increase the chance of erosion and the subsequent depletion of the seedbank in some areas and accumulation in others (Belnap *et al*. 2001). From the present study it is difficult to assess the role of erosion in the distribution of the seedbank, however one would expect some seeds to be removed from an area, along with some soil. However, Garcia-Fayos and Cerda (1997) found this not to be the case in a Mediterranean environment, where a redistribution of seeds was not affected by water runoff over the soil surface. Eerdt (1985) found that the percentage of seeds washed away depended on the mobility of the superficial sediment. In the present study, even though there was no examination for propagules in the soil collected in the erosion event of 2007, there is expected to be some movement with both soil and water flow. Venable *et al.* (2008) found in desert conditions that a steep slope can result in seeds moving downhill. As there is often a concentration of seeds under shrubs (Bullock and Moy 2004), the removal of the shrubs on the tracks would probably prevent accumulation along the slope. The small difference in the soil seedbank observed between the higher and lower areas in the undisturbed area could therefore be due to the presence of vegetation. The secondary dispersal of seeds through erosion would be reduced as the seeds would be more likely to stay in the same position as they were deposited, as water has been shown to percolate down through the soil resulting in less erosion in this area (Chapter 3).

<u>Physiological factors in seeds affecting emergence</u>

The number of seeds emerging from the samples from 2007 was much higher than from the 2006 samples at all the positions. In 2007 there were relatively large rainfall events in March (autumn) prior to April when the soil samples were collected, and these occurred after a very dry year in 2006. In contrast, there were smaller rainfall events prior to the collection of samples in 2006. Lush *et al*. (1984) suggested that some seeds may accumulate the effects of summer rains and then germinate more readily than those that have not had these conditions. This could explain the increase in emergence in 2007, particularly as the experimental conditions were the same. The number of species of plants emerging in both years reflected a similar pattern to the number of plants emerging which indicated that the factors influencing the number of emergents were related to those influencing species diversity.

Nitrate (NO_3^-) has long been known to stimulate germination (Fenner and Thompson 2005). While this stimulation occurs mostly in weedy plants, Bell *et al*. (1999) also showed that KNO_3 had a stimulatory effect on the germination of Australian arid zone winter ephemerals. *Crassula colorata*, a winter ephemeral endemic to Australia, had the highest number of seedlings emerging in the swale. This could be due to a higher number of seeds at this position and/or partially due to a higher available nitrogen concentration at this position, as the density of this species has been shown to increase significantly with the addition of nitrogen (Harris and Facelli 2003). However, the higher concentration of total nitrogen (Chapter 4) at the swale may not reflect the amount of available nitrogen. More research, such as the addition of nitrogen in field experiments and in the glasshouse to examine the effect on germination, emergence and growth of plants would be necessary to prove the breaking of dormancy by nitrate to be a major factor in explaining the differences in emergence in this study. This phenomenon also may occur in some of the species present and not others. Referring to nitrate levels could also be problematic as there is the possibility that if the concentration of the rich patches was above the saturation of the response of the plants present (and for plants adapted to growing in low nutrient soils this is probably quite low), then productivity can decrease (Facelli 2010 *pers comm*).

<u>The effect of smoked water on emergence</u>

Interestingly, the smoked water application depressed the number of seeds emerging from both the disturbed and the undisturbed areas. This was particularly apparent in the swale, but there was less effect on emergence at the crest. While Auld and Bradstock (1996) found that smoke alone consistently produced more germination than heat alone, high concentrations of smoke may have an inhibitory effect on germination for some sensitive species (Roche *et al*. 1997). *Calandrinia corrigioloides* in this study had fewer seeds emerging from the soil from the swale than the other species with the application of smoked water. As this species is known to be promoted by fire (Pate 1985), it is possibly the heat of fire that is the more important cue for germination than the effect of chemicals derived from the smoke acting as signals. These results indicate that further study is needed to assess the role that fire plays in terms of the smoke and heat components in determining the patterns of emergence in a system such as in this study.

<u>Annual vegetation in the field</u>

The study of the annual vegetation in the field aimed to assess the potential contributors to the seedbank, and if their growth pattern reflected the results of the seed emergent studies. The swale contained the highest number of species, with fewer on the slope and the crest. This pattern was probably due to the same factors possibly determining the observed difference in the number of seedlings emerging from the swale compared to the crest.

Compaction and annual emergence in the field

Compaction varied across the tracks, and would be expected to have an influence on the growth of the annual vegetation in the disturbed area. There was a microtopographic effect on the tracks with significantly more species and greater plant cover in the centre than the other positions across the tracks. The centre was not as compacted (15 kg/cm^2 at 5 cm deep in the swale and much less in the other positions along the tracks) as the soil in the wheel rut (30 kg/cm^2 at 5 cm deep at the swale and footslope and slope 17 kg/cm^2). The larger number of species and higher cover of annuals in the centre of the tracks were consistent with this position being less compacted and more exposed than the other positions. However, the benefits of exposure would have to outweigh the chance of increased desiccation. Adams *et al*. (1982) and Vollmer *et al*. (1976) found a reduction in plant establishment in areas frequented by off road vehicles, with larger seasonal rainfall lowering the impact of compaction. Soil strength, which is the amount of force required to move or rearrange soil particles affects the capacity of emergence and soil water content is also an important determining factor in the germination and emergence of seedlings (Collis-George and Yoganathan 1985). In the present study the year the annual vegetation was assessed in the field had a very high spring rainfall of 124.9 mm compared to the following two springs with 4.8 mm and 15.4 mm respectively. Thus, in a system as variable in rainfall as this semi-arid ecosystem, the impact of compaction on annual seedling emergence and growth is likely to be affected correspondingly if the soil strength increases.

Seasonality

In this study enhanced emergence was found in the disturbed areas, particularly in the swale and in the centre of the tracks. This was not found by Hobbs (1989), who observed that native annual species did not germinate preferentially in disturbed areas with a higher nutrient availability. A limitation of soil seedbank studies is that they may not necessarily reflect the existing flora observed above ground and may not reveal the actual biodiversity in the ecosystem. For example Fox (1989) found in a study of a range of sites monitored over six years that the most arid site with *Triodia* understorey was the most species rich, with 96 species recorded and only a fraction present at any one time. Therefore, to better assess the regeneration potential after disturbance emergence studies over a number of years would be more beneficial.

Perennials and dispersal

There were no perennials emerging from the seedbank, which is similar to studies conducted by Vlahos and Bell (1986) in a jarrah forest. As the regrowth of any perennial vegetation after clearance is the most important factor in the regeneration of the disturbed area of the tracks, the dispersal of propagules into the area of disturbance is a factor in determining the succession of vegetation growth. However, the role of this dispersal of the perennials, their contribution to the soil seedbank and subsequent emergence in the disturbed area is a complicated issue. Apart from the lack of perennial seedlings emerging from the seedbank there were also few seedlings in the field in both the disturbed and the undisturbed areas. The seeds of mallee eucalypts are retained in the canopy (Wellington and Noble 1985), until conditions are right for their germination. However, Wellington and Noble (1985) found in their study on *Eucalyptus incrassata* that the recruitment of seedlings of mallee eucalypts was very limited, even following fire. In mallee vegetation growth from lignotubers is a dominant means of regeneration, and so recruitment from seeds could be limited. When eucalypts drop their seeds they can be collected in great quantity by ants that are generally not regarded as harvester ants and have been found in a great number in ant nests (Berg 1975). The assessment of the dispersal methods of the species present showed that more plants were dispersed by a combination of wind and fire than by other strategies, which would not limit the presence of seeds on the tracks. From this study the recruitment of perennials in the disturbed area is likely to be more affected by other environmental factors being adequate for their germination, emergence and growth. Even with the most ideal environmental conditions and the potential for growth from seeds on the tracks, the composition of the vegetation would possibly be influenced by any changes to ant behaviour due to disturbance as most species are dispersed or eaten by ants.

Removal of seeds by ants

There were no differences in the removal of seeds by ants between the disturbed and the undisturbed areas or between positions along the tracks, which reflects the lack of differences in ant behaviour and possibly abundances. This suggests a lack of differences in ant activity. This contrasts with other studies where disturbance negatively influenced the diversity and abundance of ants (Graham *et al*. 2004). The presence of tracks has been found to influence the distribution of harvester ants in a study in Colorado in the American Southwest where they preferentially located their colonies near trails (Terranella *et al*. 1999).

Most of the seeds transported by ants in this study were acacia seeds and to a lesser extent eucalypt seeds. The species of ant present in the ecosystem would have been an important factor in seed dispersal, as eucalypt seeds in other studies have been shown to be removed to a large extent (Anderson 1982, Wellington and Noble 1985). The ants benefit from the acacia seeds due to the elaiosome, but little is known about the reasons for transporting the eucalypt seeds as they do not have any apparent elaiosome and are hard and dry. As there were more myrmecochorous perennial species present the role of ants in plant recruitment is probably vital for some species and if ant behaviour, which is extremely complex, is affected by disturbance this recruitment would be affected also. However, this was not indicated in this limited study.

To conclude, the emergence of annual seedlings from the seedbank may be affected by compaction, topography, vegetation cover and transport processes of water and soil (Figure 5.12).

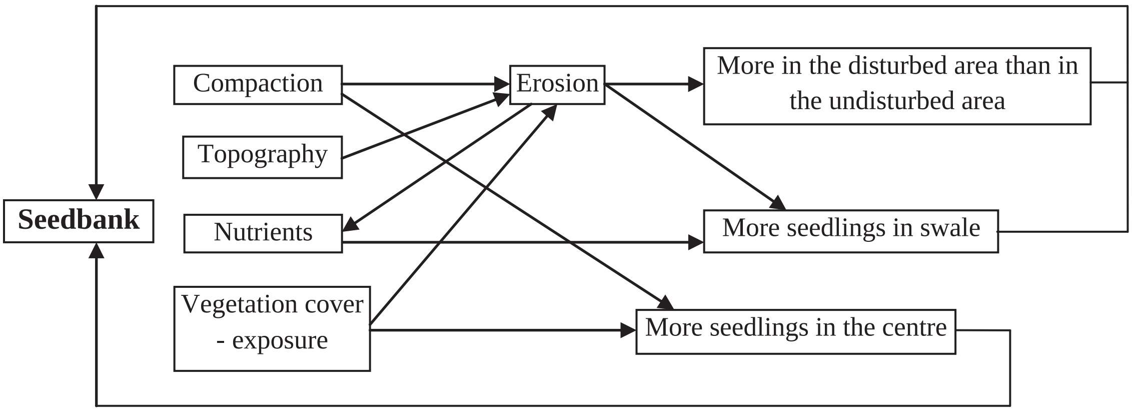

Figure 5.12 Model constructed from this study with arrows showing effects of the environment on the seedbank

The community of annual plants was the only contributor to the emerging seedbank as no perennial plants emerged in the seedbank experiments. Therefore, the seedbank composition may not be as important as resprouters in the possible regeneration of the perennial vegetation in this ecosystem. This was also found in a study of the regeneration of *Acacia* spp. in New South Wales following grading along the roadside (Spooner 2005). The influence of the topography on the growth of annual seedlings could reflect the potential growth pattern of weeds if their seeds were introduced into the area.

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Chapter 6 Regeneration Potential

Introduction

The establishment of perennial vegetation is an important factor in the rehabilitation of an ecosystem after disturbance. The type and intensity of the disturbance will also determine the regeneration potential of this vegetation, as environmental and biotic factors are changed. The greater the severity of disturbance the slower the rate of recovery, as Sims (1977) found in the arid west of the United States and, as recovery is slow in these areas anyway, this is significant. An increase in soil compaction has been found to be one of the factors related to disturbance from the clearing of mineral exploration tracks (Chapter 3). The re-establishment of vegetation can be adversely affected by this compaction, which has been shown to result in an increase in soil strength, and the rate of both emergence of plants and root elongation can be reduced (Kozlowski 1999). If there is a compact zone at shallow depths there is a limitation of root development and a resultant water stress on plants (Unger and Kaspar 1994). This is particularly important in areas with very low rainfall where plants depend only on precipitation, as in semi-arid areas. A penetrating resistance of 2 MPa (20.4 kg/cm^2) is often used as a threshold beyond which the growth of crop plants become severely restricted (Taylor *et al*. 1966, Day and Bassuck 1994). However, plants growing in natural conditions would be more adapted to harsher conditions, and so may be able to penetrate harder substrates. There have been few studies on the effect of compaction on the ability of native species to regenerate (Bassett *et al.* 2005). Smith *et al.* (2001) have shown restriction of growth in four Australian tree species with a 60% reduction in root growth at 1.5 MPa. In the present study the soil compaction was approximately 1.96 MPa (20 kg/cm^2) in the wheel rut in the swale at the depth 0 – 3 cm, which increased to 3.92 MPa (40 kg/cm^2) in the 6 – 15 cm range (Chapter 3). Therefore, the growth of perennial seedlings would be expected to be curtailed in this position.

The vegetation composition and the characteristics of different growth forms in the undisturbed situation is an important factor to be taken into account when determining the recruitment potential after disturbance. Two thirds of mallee vegetation regenerates by resprouting (Bell 2001) with adaptations for growth from underground lignotubers and epicormic buds to enable establishment after fire (Groves 1994). There have been many studies conducted on regeneration after fire in the mallee (Wellington and Noble 1985), but little is known on regeneration after clearing. Vesk *et al*. (2004) found fire to have a higher intensity of disturbance than clipping, but this had little effect on the sprouting ability of the semi-arid species studied, which they found had a strong (grasses and multi-stemmed plants) and weak ability (chenopods) to resprout. It is commonly thought that with short intervals between disturbances there is greater chance of extinction of non sprouters versus resprouters. However, there is also a chance of vegetation not regenerating when they have a weak ability to resprout (Vesk *et al*. 2004). The establishment of woody seedlings through seed germination is subject to competitive pressures, such as between angiosperm herbs and shrubs and conifer seedlings (Bond 2008). This is common and significantly affects conifer growth and survival (Bond 2008). Facelli and Pickett (1991c) and Facelli (1994) also found that herbaceous vegetation can directly compete with woody seedlings. Seedling emergent rates in an oldfield situation in New York have also been shown to be lower under annuals and biennials (Gill and Marks 1991).

Reshooting from mallee stumps may be encouraged by an increase in light once the overhead canopy is removed (Ryan 2005). Growth of *E. obliqua* from seeds has been found to be greater after the overstorey was cleared, than from lignotubers (Walters and Bell 2005). The amount of litter cover will affect the establishment, growth and species richness of vegetation (Facelli and Pickett 1991c). Litter influences shading, temperature, evaporation, decomposition rates, microbial activity, nutrient cycling and germination (Vasquez *et al*. 2008). The presence of litter can increase humidity in the proximity of seeds, as has been shown with the increased emergence of *Eucalyptus obliqua* seedlings in the presence of litter (Facelli 1999, Ladd and Facelli 2008). Litter influences many processes and the growth of different species (Peterson and Facelli 1992) and different functional groups (Ladd and Facelli 2008). The species responses can be difficult to predict, but overall effects in various systems are more predictable.

There haven’t been any studies on the influence of litter in semi-arid mallee ecosystems in disturbed versus undisturbed environments. As there is more litter in the undisturbed area than the disturbed area (Chapter 4) this could also be influential on seedling establishment along the tracks. This study, therefore provides an opportunity to assess the possible impact on the composition of the vegetation where there has been a disturbance resulting in different litter coverage. The presence of litter would enable seeds to accumulate due to the microsites in the litter and with the evaporation rates being reduced seedling growth should be promoted (Facelli and Pickett 1991b). However, litter can also inhibit growth due to shading, creating a physical barrier and absorbing moisture from rainfall, depending on the size of the rainfall event (Facelli and Pickett 1991b). The presence of litter can also effect competition through delaying the rate of establishment of competitors (Ladd and Facelli 2008).

Disturbances can favour the invasion by certain species of plants that can in turn trigger further changes in the system (Tippets 1998). Deposition of nutrient rich material in swales due to erosion in cleared areas could encourage growth of weedy species that require disturbance and/or nutrient enrichment (Hobbs and Atkins 1988). Weeds can subsequently compete with local species for resources. They can alter erosion and sedimentation and change nutrient dynamics (Muyt 2001). They can also increase fire potential and the incidence of pest animals, insects, pathogens and diseases (Muyt 2001). Although successful plant invasions are often associated with increased disturbance (Hobbs 1989, Rejmanek 1989, Hobbs and Huenneke 1992), there are also circumstances where the frequency or intensity of a natural disturbance is relatively low yet invasion of competitively superior non-natives may be promoted (Hobbs and Huenneke 1992).

Weeds can be introduced by vehicles, footware, blown in by the wind, in water flows and in the faeces and fur of animals (Muyt 2001). Roads provide an ideal way for non-native species to move into areas as they provide an altered habitat, stress or remove native species, and enable greater movement of people and other possible vectors of dispersal (Trombulak and Frissell 2000, Myers and Bazely 2003). Once weeds are introduced, even if they may not be apparent, the seeds may lie dormant in the seedbank waiting for the necessary conditions for their germination. They may then become a major problem as their eradication is often very difficult, and they can change the whole ecosystem dynamics by out-competing the native species. Thus, as Hobbs and Huenneke (1992) suggested, a decline in native species diversity may be the result of a modification of the historical disturbance regimes.

The role of competition between annual plants and herbaceous vegetation and perennial plants in seedling establishment could be a determining factor in the plant composition regenerating in the disturbed area. Possibly competition could partially explain why more annual plants emerged in the swale in the disturbed area than in the swale in the undisturbed area (Chapter 5). There is a high likelihood of weeds being introduced into this otherwise little disturbed area of Pinkawillinie CP. The clearance of tracks can also provide pathways for native and non-native grazing animals, which can provide further place stress on the successful growth of perennial seedlings to maturity.

The vegetation of Pinkawillinie CP in the area of this study is composed of an overstorey and mid layer consisting mainly of *Callitris verrucosa, Eucalyptus socialis, E. incrassata* and *Melaleuca uncinata* (Chapter 5). There has been anecdotal evidence that the obligate seeder *Callitris verrucosa*, did not regenerate readily when flattened by the roller used to make exploration tracks (Drown *pers. comm.* 2005). Drown *pers. comm.* (2005) also observed that the *Melaleuca* spp. vary in their regeneration capabilities, some species being more vulnerable to disturbance than others. The mallee eucalypts and *M. uncinata* can both regenerate from underground lignotubers and epicormic growth (Specht 1966). Some young plants of *M. uncinata*, however, may not have developed epicormic buds and these are incapable of resprouting (Bradstock 1989). Anecdotal evidence also suggested that *Triodia* ssp., the dominant species in the ground layer (Chapter 5), do not easily regenerate along tracks (Drown *pers. comm.* 2005). More information on the capacity of *Triodia* ssp. to regenerate after disturbance is needed, as activities associated with mining, including mineral exploration, are the most important form of land use in areas where hummock grasslands predominate (Fox *et al*. 1999).

While there is some anecdotal information, there have been few studies analysing the nature of the regeneration of vegetation after clearance in mallee communities, and none on the impact of linear disturbance.

This chapter aims to answer the questions:

- How could the presence of litter potentially affect seedling growth between the disturbed and undisturbed areas and between topographical positions?
- Was there a difference in the potential for weed invasion between different sections along the tracks and between the disturbed and the undisturbed areas?
- How successful was the regeneration of perennial growth on the tracks?
- Were there differences between species regenerating along the tracks and was the topographical position an important factor?
- Were there differences in survivorship and growth between the disturbed and undisturbed areas or topographical position when seedlings were planted and did grazing play a role in their growth?

Methods

The data sets were collected from three tracks at four positions across the tracks; centre, wheel rut, shoulder and undisturbed (microtopography) from four positions along the tracks; swale, footslope, slope and crest (topography) as shown in Chapter 3 (Figure 3.2). Details of the location of tracks and how they were created are given in Chapter 2.

6.1 Effect of litter on seedling growth

In April (autumn) 2007 quadrats (60 cm x 30 cm) with chicken wire placed on top were constructed to hold in litter (3 replicates with litter and 3 without litter). These were placed in the disturbed and the undisturbed areas at the swale and crest of the 3 tracks resulting in 36 quadrats. The litter consisted of approximately 500 g/m^2 of 50% small sticks and 50% leaf litter mainly from eucalypts and *Triodia* spp. collected from nearby. This represented a high amount of litter cover as commonly found in the field (Stokes 1993). Seedling growth was scored after 6 months in October (spring). There were a large number of seedlings in a number of the quadrats, and so the naturally established seedlings were counted for each of the species in a 20 cm x 20 cm quadrat placed in the centre of the larger quadrats and the chicken wire and litter were removed to enable this.

6.2 Weed invasion capacity

Carrichtera annua is a common annual weed species in the semi-arid areas in the north of South Australia. A phytoassay was conducted to assess the potential for *C. annua* to invade the area using soil collected at the crest and swale from each of the tracks with five replicates from each of the four positions across the tracks and in the undisturbed area in October (autumn) in 2006. These samples were placed in pots in the glasshouse and three seeds of *C. annua* planted in each. These were watered periodically. Once the plants were mature enough to set seed their above ground biomass was harvested, dried and weighed.

6.3 Survivorship and growth of young perennial plants

Young perennial plant survivorship and growth in the disturbed area along the tracks was assessed by labelling five plants closest to three randomly placed points at each of the swale, footslope, slope and crest on each of the tracks. This was done in September (spring) 2006 and the height, width and identity were recorded. Measurements were taken again after 8 and 28 weeks in April 2007 with the number of deaths also recorded.

6.4 Growth of planted native seedlings in the field

Eucalyptus incrassata was used to assess seedling growth and predation as it is widespread throughout southern Australia. In June (winter) 2007, 216 seedlings of *Eucalyptus incrassata*, obtained from Belair National Park nursery at approximately 20 cm high, were planted six each to cages of 1 cm^2 square mesh to prevent predation. These and controls of six plants without cages were placed at each of the swale, slope and crest in the wheel rut on the tracks and in the undisturbed area on each of the three tracks, resulting in 18 treatments (108 plants) and 18 controls (108 plants). The height of each of these was measured and the number of leaves counted, noting the basal leaves separately from the others along the main stem. They were watered on planting and the rainfall monitored so as to not let them dry out if there was no rain, but after four weeks there had been consistent rain. After 16 weeks the seedlings were measured and the number of leaves counted. The plants were harvested after 16 weeks and their biomass determined by being cut at ground level, dried and weighed. This was the measure for growth used in the analysis.

Statistical Analyses

The data sets were analysed with the appropriate statistical test for the analyses of variances performed and the role of the dispersion of replicates determined as in Chapter 3.

Effect of litter on seedling growth

The differences in the number of plants and species emerging between quadrats with litter and those without litter were assessed when nested within across and along positions and tracks, between across positions when they were nested within along positions and tracks and differences between along positions when they were nested within tracks and between tracks using three replicates. The data sets were not normal for both the number of plants and the number of species and the variances for the number of plants were heterogeneous for the positions along the tracks and for the tracks, and for the number of species were homogeneous.

Weed invasion capacity

The capacity for weed invasion was tested using the differences in the weight of *Carrichtera annua* between the positions across the tracks when nested within the positions along the tracks and tracks, between the positions along the tracks when nested within tracks and between tracks, with five replicates. The data set was not normal and the variances were heterozygous for the positions along the tracks and for the tracks.

Survivorship and growth of perennial plants

The data sets were assessed for differences between: the number of live plants after 8 weeks and after 28 weeks; the number of live plants after 28 weeks and the number of these that exhibited growth; when nested within the number of young plants along the tracks and tracks, and the differences between positions along the tracks when nested within the tracks and between the tracks with five replicates. The data set was not normal and the variances were all heterogeneous. The alive and dead species were scored, and which ones explained the differences between the positions along the tracks were determined using Multi-Response Permutation Procedures (MRPP) with a Sorenson distance measure.

The data sets were also assessed for differences in terms of the number of young plants of the main grass species (monocots) – *Austrodanthonia* sp., *Austrostipa* sp. and *Triodia* sp. grouped together and the number of plants not in this group (mainly dicots with *Scheonus subaphyllus, Lepidosperma lateralis* – however, these two species had very low numbers and this group is referred to as dicots) when nested within the positions along the tracks and the tracks, and the differences between positions along the tracks when nested within the tracks and between the tracks with five replicates.

Growth of planted native seedlings in the field

The data sets were assessed for differences in the amount of growth (measured in gm. of dry weight at the end of the experiment) between; the disturbed and undisturbed areas when nested within caged/uncaged, positions along the tracks and tracks, the caged and uncaged seedlings when nested within the positions along the tracks and tracks, between the positions along the tracks when nested within the tracks and between the tracks. The data set was normal and all the variances were homogeneous.

Results

6.1 Effect of litter on seedling growth

In the pairwise comparisons there were more seedlings emerging in the swale than the crest (PERMANOVA version 1.6, $F_{3,71}$=15.8, p<0.001) in Track 2 (t=3, p<0.0125) and Track 3 (t=3.9, p<0.0125). There were also more species in the swale and the crest (($F_{3,71}$=23.44, p<0.01) in Track 3 (t=5.36, p<0.01) (Figure 6.1).

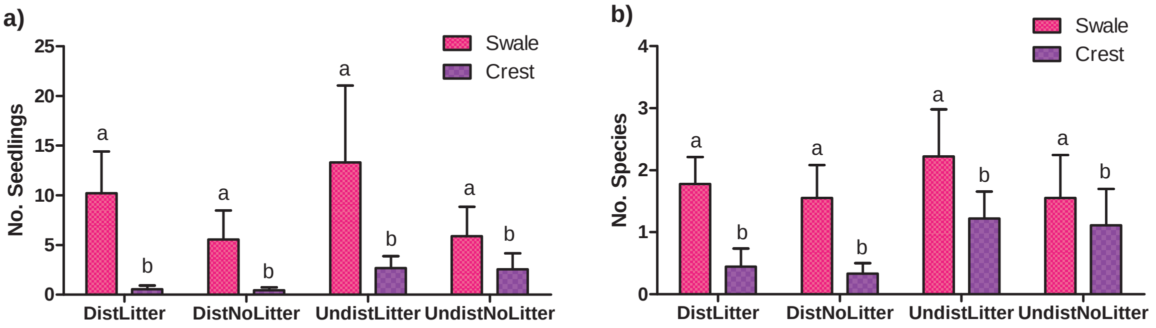

Figure 6.1 a) Seedlings and b) Species growing with and without litter along the tracks and in the disturbed and undisturbed area (±95% CI, n = 9, 3 tracks combined) - letters denote differences at p<0.05 level

6.2 Weed invasion capacity

There was less biomass of *Carrichtera annua* in the soil from the centre than the wheel rut ($F_{18,119}$=2.02, p<0.017) in the swale of Track 1 (t=4.1, p<0.013). There was a higher biomass of *Carrichtera annua* growing in soil from the swale than from the crest (PERMANOVA version 1.6, $F_{3,119}$=71.5, p<0.01) (Table 6.1) in Track 1 (t=11.06, p<0.01) and Track 2 (t=6.36, p<0.01) (Figure 6.2 a), b)). The interaction between the biomass of *Carrichtera annua* in the positions along the tracks and the positions across the tracks was significant (PERMANOVA version 1.6, $F_{3,39}$=22.4, P<0.01).

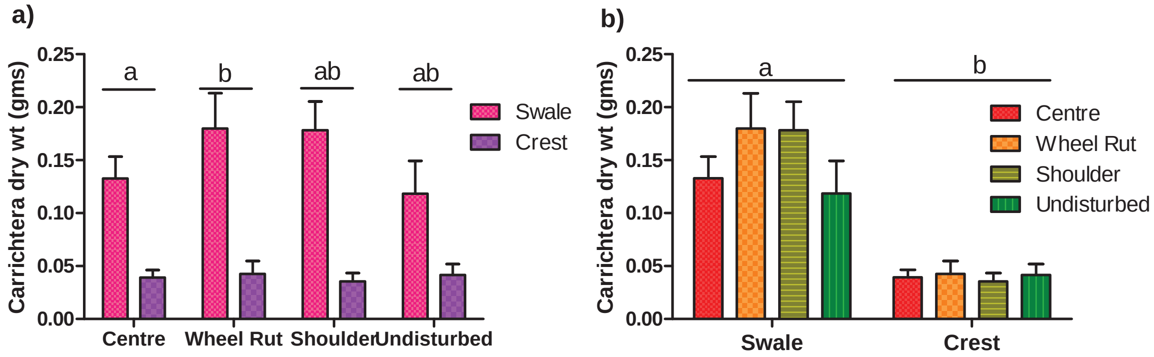

Figure 6.2 Biomass of *Carrichtera annua* (gms.) growing in soil from a) across and b) along the tracks (±95% CI, n = 15, 3 tracks combined) - letters denote differences at p<0.05 level)

6.3 Survivorship and growth of young perennial plants

No. of plants surviving after 8 and 28 weeks

There were no significant differences between the disturbed and the undisturbed areas or between the positions along the tracks. There were fewer surviving plants after 8 weeks and less again after 28 weeks (PERMANOVA version 1.6, $F_{24,179}=6.97$, $p<0.01$). There were more young plant mortalities at eight weeks in Track 1 in the swale ($t=5.88$, $p<0.001$), the slope ($t=4.81$, $p<0.01$) and the crest ($t=4.81$, $p<0.01$), in Track 2 in the footslope ($t=4.47$, $p<0.01$) and slope ($t=6.33$, $p<0.01$) and in Track 3 in the slope ($t=6.53$, $p<0.01$). There were more mortalities after 28 weeks than after 8 weeks in Track 1 in the swale ($t=3.2$, $p< 0.05$) and in the slope ($t=3.16$, $p<0.05$) and in Track 2 in the footslope ($t=3.67$, $p<0.05$) (Figure 6.3).

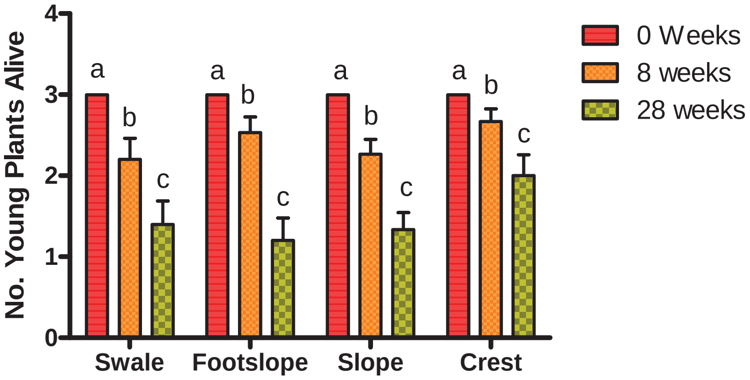

Figure 6.3 Number of surviving young perennial plants along the tracks in the disturbed area (±95% CI, n = 15, tracks combined) - letters denote differences at p<0.05 level

No. of young perennial plants surviving and number that had grown after 28 weeks

There were no significant differences between the surviving plants and the number of these that had grown after 28 weeks (Table 6.1). There were more plants surviving and growing at the crest than at the swale ($t=3.28$, $p<0.05$), footslope ($t=3.5$, $p<0.01$) and slope ($t=4.12$, $p<0.01$) (Table 6.1 and Figure 6.4). Track 1 had less survival and growth than Track 2 ($t=2.78$, $p<0.05$) and Track 3 ($t=4.16$, $p<0.01$) (Table 6.1).

Table 6.1 The results from the PERMANOVA version 1.6 analysis with the scores for the number of live young perennial plants after 28 weeks and the number of these that exhibited growth; when nested within the number of plants along the tracks and within the tracks, and the differences between positions along the tracks when nested within the tracks and between the tracks with five replicates.

PERMANOVA 1.6	df	SS	MS	F	P
Tracks	2	15.27	7.63	8.77	0.002
Along (Tracks)	9	21.4	2.38	2.73	0.01
Week/Growth(TrxAlong)	12	3.2	0.27	0.31	0.97
Residual	96	83.6	0.87		
Total	119	123.47			

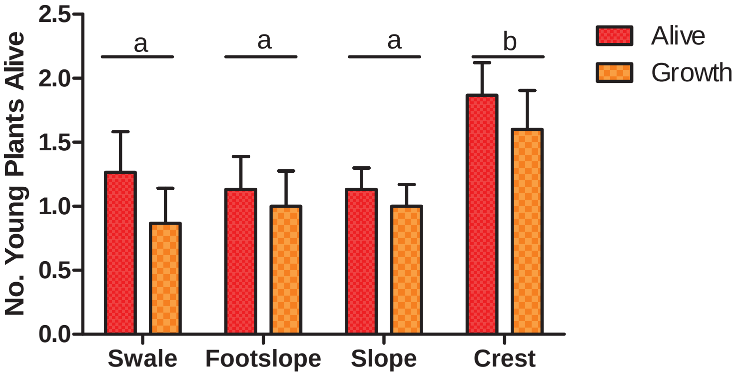

Figure 6.4 No. of surviving young perennial plants and the number that had grown after 28 weeks along the tracks (±95% CI, n = 15, 3 tracks combined) - letters denote differences at p<0.05 level

Analysis of species contributing to any differences in survival and topographic position

Young *Melaleuca uncinata* plants were the main contributors to the difference in survival with significantly more alive than the other perennial plants ($p<0.001$). The next most important contributors with significantly more dead plants than other young plants were grasses *Austrodanthonia* sp., *Austrostipa* sp. ($p<0.01$) and *Triodia* spp. ($p<0.05$) and *Comesperma scoparia* had significantly more plants surviving ($p=0.0508$) (Table 6.2).

Table 6.2 MRPP analysis showing the species explaining the differences between the numbers of alive and dead plants

Species	**Survival (Maxgrp)**	**p***
Melaleuca uncinata	Alive	0.001
Grasses	Dead	0.01
Triodia spp.	Dead	0.05
Comesperma scoparia	Alive	0.05
Bertya mitchellii	Dead	0.120
Leucopogon cordifolius	Dead	0.121
Hibbertia riparia	Alive	0.129
Eucalyptus sp	Dead	0.238
Maireana pentatropis	Alive	0.255
Leptospermum coriaceum	Alive	0.371
Babingtonia behrii	Alive	0.746
Scheonus subaphyllus	Dead	1
Lepidosperma lateralis	Alive	1
Calytrix sp.	Alive	1
Calytrix tetragonia	Alive	1

The number of grass plants was the most important factor in explaining the differences between the sections along the tracks and was significantly higher in the swale than the other plants ($p<0.001$). *Hibbertia riparia* was significantly more abundant at the crest ($p<0.01$). *Babingtonia behrii* was significantly more abundant in the footslope ($p<0.01$). *Triodia* sp was significantly more abundant in the slope ($p<0.05$) and *Melaleuca uncinata* was significantly more abundant in the crest ($p<0.05$) (Table 6.2).

Table 6.3 MRPP analysis showing the species explaining the differences between the numbers of plants at positions along the tracks

Species	**Along (Maxgrp)**	**p***
Grass	Swale	0.001
Hibbertia riparia	Crest	0.005
Babingtonia behrii	Footslope	0.008
Triodia spp.	Slope	0.013
Melaleuca uncinata	Crest	0.033
Scheonus subaphyllus	Swale	0.056
Eucalyptus sp	Crest	0.064
Bertya mitchellii	Footslope	0.198
Comesperma scoparia	Slope	0.393
Leptospermum coriaceum	Slope	0.41
Maireana pentatropis	Swale	0.616
Lepidosperma lateralis	Footslope	0.621
Leucopogon cordifolius	Swale	0.907
Calytrix sp.	Crest	1
Calytrix tetragonia	Footslope	1

Monocot and dicot plant distribution and survival

There were significantly more dicots than monocots for the initial scores along the tracks (PerMANOVA, $F_{12,119}=3.77$, $p<0.01$) with more monocots than dicots in the swale of Track 1 ($t=3.89$, $p<0.05$), more dicots than monocots in the crest of Track 2 ($t=6.35$, $p< 0.05$) and more dicots than monocots in the slope of Track 3 ($t=4.95$, $p<0.01$) (Figure 6.5 a), b)).

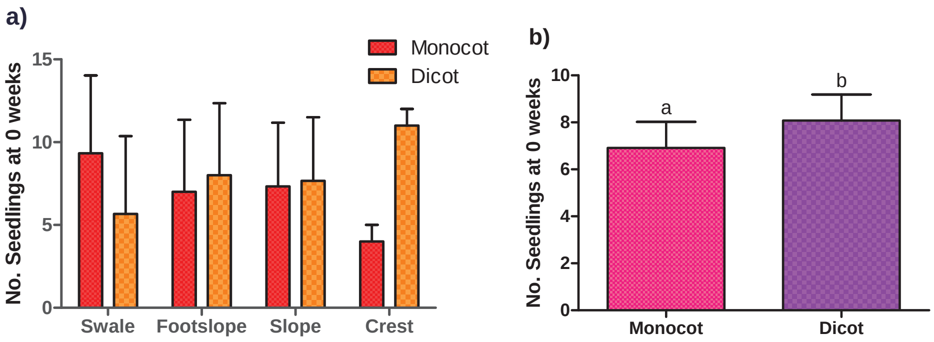

Figure 6.5 a) No. of monocot and dicot plants along the tracks (swale, footslope, slope and crest) at 0 weeks and b) No. of monocot and dicot plants also at 0 weeks - letters denote differences at p<0.05 level

There were more dicots alive after 28 weeks than monocots along the tracks (PerMANOVA, $F_{12,119}=2.96$, $p<0.01$) in the swale ($t=4$, $p<0.05$) and in the slope ($t=3.21$, $p< 0.05$) of Track 2 (Figure 6.6 a), b)).

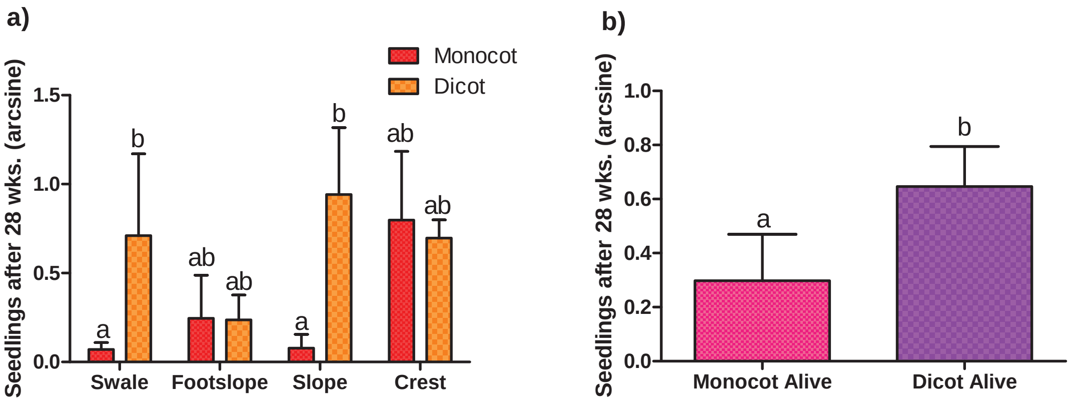

Figure 6.6 a) No. of monocot and dicot plants along the tracks (swale, footslope, slope and crest) at 28 weeks and b) No. of monocot and dicot plants also at 28 weeks - letters denote differences at p<0.05 level

6.4 Growth of planted native seedlings in the field

There were no significant differences in the growth of *Eucalyptus incrassata* seedlings (measured in grams of dry weight at the end of the experiment) between the disturbed and the undisturbed areas, and between the caged and uncaged treatments.

There were differences at positions along the tracks (PerMANOVA version 1.6, $F_{6,215}=8.36$, $p<0.01$) with less growth in the swale than the slope ($t=2.99$, $p<0.01$) and more in the swale than the crest ($t=3.71$, $p<0.01$) in Track 1, more in the swale than the slope ($t=2.98$, $p<0.01$) in Track 2 and more in the swale than the slope and crest in Track 3 ($t=4.25$, $p<0.01$) and ($t=4.58$, $p<0.01$) respectively (Figure 6.7 a), b)).

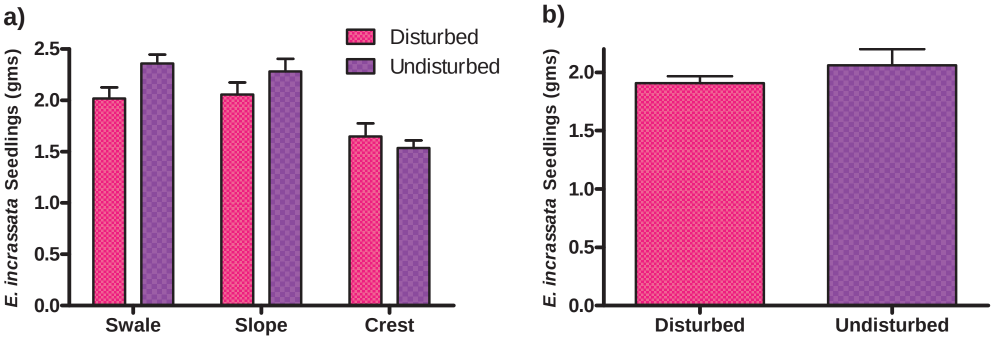

Figure 6.7 The amount of growth of *E. incrassata* seedlings (measured in grams of dried weight) at a) positions along the tracks and b) the disturbed and undisturbed area (±95% CI, n = 36, tracks, caged/uncaged combined)

There was more growth in the undisturbed than the disturbed areas in Track 1, uncaged, swale (t=3.78, $p<0.01$) and slope (t=2.99, $p<0.05$) (Figure 6.8 a), b)).

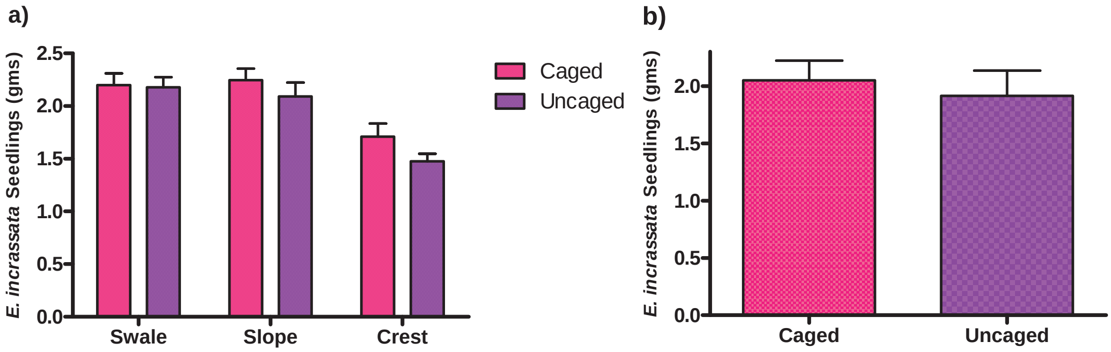

Figure 6.8 The amount of growth *E. incrassata* seedlings (measured in grams of dried weight) at positions a) along the tracks b) caged and uncaged (±95%CI, n = 36 tracks, dist/undist combined)

Discussion

The topography of the field site was the most important contributor to differences in the growth and distribution of plants, including seedling number and species (with and without litter), weed invasion capacity, the establishment of young perennial plants and perennial plant growth. There was greater growth of seedlings in the field and *Carrichtera annua* in the glasshouse in the swale compared with the other positions along the tracks. This difference in topographical position along the tracks was much more influential than differences between disturbed and undisturbed areas, where these were compared. This was particularly the case for seedlings in the field growing with and without litter, *Carrichtera annua* growth in the glasshouse and growth of planted seedlings in the field. That is all aspects of this study except for the establishment of perennial plants.

The presence of litter in the quadrats appeared to have no significant effect on the emergence and growth of seedlings overall. Even though there was more natural litter in the undisturbed area than in the disturbed area a difference was not observed in the soil carbon distribution (Chapter 4). This could suggest that little decomposition was occurring, which is extremely slow in these systems. Other effects of litter besides decomposition, such as moderation of soil temperature and reduction in evaporation operate across shorter temporal scales and are important, even if litter accumulation is transient (Facelli and Pickett 1991b), c)). However, any influence of these factors was not apparent in this study.

The potential invasion of weeds as assessed by the phytoassay of *Carrichtera annua* growth in soil samples was greater at the swale than at the crest, which reflected the pattern of annual seedling growth. There were no significant differences between the disturbed and the undisturbed areas. As the phytoassay using *Carrichtera annua* was run in the glasshouse, the number of seeds, water and light were not limiting factors, whereas the properties of the soil samples were. As shown in Chapter 4 there was more nitrogen and potassium in the swale than on the slope. This nutrient distribution would possibly explain the differences in the growth of *C. annua* as many invasive exotic species are adapted to higher nitrogen levels than native species (Rejmanek and Richardson 1996). They can exploit nitrogen faster than later successional native species (Fogarty and Facelli 1999). However, there was also more growth of native annual seedlings in the field and more emergence of seedlings from the soil seedbank in this position (Chapter 5). Soil seedbank studies (Chapter 5) and field observations did not show the presence of weeds in the area. This does not mean, though, that seeds were not present in the seedbank or that the conditions changed with disturbance were not potentially conducive to weed growth. The pattern observed in the phytoassay would be exacerbated in the field if there was an introduction of weed seeds, as their accumulation and emergence in the swale would likely be similar to that of the indigenous plant seeds. Therefore, if weed seeds were introduced there is a greater chance of the proliferation of weed growth in the swale. O'Connor *et al*. (2002) showed that *C. annua* growth exhibited a significant increase in above ground biomass than the control when there was no colonisation of arbuscular mycorrhizae after a fungicide was added. As a large number of Australian native plants require arbuscular mycorrhizae for healthy growth any changes in the presence of these fungi in the soil could influence the composition of the vegetation particularly when weed seeds are present, depending on their dependence on this symbiosis.

The survival rate for the young perennial plants on the tracks was very low. Mortality was different for different species resulting in a change in their relative abundances. Initially, there were more monocots than dicots in the swale and more dicots than monocots in the crest, but after 28 weeks the swale and slope both had more dicots surviving than monocots. Materechera *et al.* (1991) studied a number of species and found dicots to have longer and thicker roots in more compacted soil that monocots. The swale showed a higher compaction than the other sections along the tracks (Chapter 3), which may have caused the mortality of monocots growing in this position as shallow rooting systems are impacted upon by compaction (Lull 1959). This would then override the benefits of higher nutrients (Chapter 4) and moisture availability (Chapter 3) in this position. The drought conditions in the year in which this study was conducted would have exacerbated the negative effect of compaction on growth, as the soil water held in the top layers possibly dried out fast (Chapter 3). Harradine and Whalley (1981) and Specht and Rayson (1957) found that the monocots *Austrodanthonia bipartite* and *Austrostipa semibarbata* respectively both have extensive root systems in the top 20 cm of soil. These shallow roots result in these species being more susceptible to drought, while deep rooted perennials can utilise a greater range of soil water (Pook and Costin 1971). There had been a large rainfall event with accompanying soil movement along the slope, as this was the main area of soil collection (Chapter 3), just before the final scores for the perennial seedling survival and growth were collected, which appeared to have caused the uprooting of the shallow rooted monocots. The low survival rate of *Triodia* spp. seedlings, which grew mainly on the slope, could have been due to this erosion. However, there is a high rate of seedling mortality documented in this type of environment mainly due to favourable weather for establishment occurring infrequently (Meyer and Pendleton 2005). The development of roots of *Triodia* spp. is closely correlated to the amount of water available (Burbridge 1945). Even though *Triodia* spp. can resprout or grow from seeds (Rice and Westoby 1999), if the plants on the tracks were grown from seeds, they would not have access to the extensive root system of the parent plant for water, nutrients and anchorage. Therefore, if the establishment is by seed germination and emergence, the seedlings would be more vulnerable to environmental factors. The high survival of *M. uncinata* was possibly due to resprouting from lignotubers below the surface. *M. uncinata* had a lower survival at the crest, which was also observed by Bradstock (1989). Bradstock (1989) found that the survival of young plants of *M. uncinata* after fire varied according to their topographic distribution, with those on or near the dune crests having a lower survival rate than those on the lower slopes of the dunes. The other perennial dicot on the tracks with high survival was *Babingtonia behrii*, which was not expected, as this species is known to be drought sensitive and to have a shallow spreading root system (Florabank 2009). The other genera present *Hibbertia* and *Calytrix*, have a shallow tap root down to 30 to 40 cm (Specht and Rayson 1957), which could access moisture deeper down in the soil profile even in dry conditions.

The growth of *Eucalyptus incrassata* seedlings planted in the field showed no significant differences between the disturbed and the undisturbed areas or any consistent pattern along the tracks. In the caged and uncaged treatments of the growth of *E. incrassata* there were no differences due to grazing between the disturbed and undisturbed areas or along the tracks. There was some grazing of perennials, particularly *Comesperma scoparia* observed on the tracks. The increased grazing within conservation areas due to increased access is a potential problem and *Comesperma confertum* has been shown in a previous study to be significantly less in an area outside of an enclosure in a study in Perup Nature Reserve in Western Australia (Shepherd *et al.* 1997). The main grazers in this study were shown to be the western grey kangaroo, which would be present in this area.

The characteristics of the recruitment of perennial plants and the potential growth of weed species are the result of topographical features, which affect the physical and chemical characteristics of the environment. Even though few differences between the disturbed and undisturbed areas were apparent, changes in the ecosystem over time along the tracks are likely to increase, and so producing changes to the functioning of the ecosystem. The regeneration potential in the disturbed area is likely to be reduced due to these changes.

§

Chapter 7 Microbiota of the Soil – Soil Crust and Arbuscular Mycorrhizae

Introduction

The microbiota in soil plays a significant role in the processes of a functioning ecosystem. There is scant knowledge of the composition of these communities, particularly in non-agricultural systems. These micro-organisms affect the physical and chemical characteristics of the soil and plant communities in terms of the soil structure, nutrient recycling and vegetation composition and health. Soil crusts contribute to the control of nutrient and water movement (West 1990) and seedling germination and emergence (Facelli and Springbett 2009), while arbuscular mycorrhizal fungi (AMF) play a major role in transference of nutrients to plants, soil aggregation and protection against drought stress (Dodd 2000). AMF are important and pervasive, particularly in environments with infertile soils and limited rainfall such as those in semi-arid Australia (Smith and Read 1997). Crusts can consist of organic elements or be of a physical or chemical nature. The stabilisation of the soil surface of arid and semi-arid systems occurs via thin biological crusts made up of a complex mix of cyanobacteria, lichens, algae, liverworts, fungi, bacteria and mosses (West 1990). These microbiota are essential components of ecosystem functioning, particularly in areas where they are a major component of soils, as in southern Australia (Eldridge 2001).

In addition to providing stability, crusts also increase nutrient availability through biological nitrogen fixation and mineral chelation (Eldridge and Greene 1994, Darby *et al*. 2007). They produce complex effects on water infiltration and runoff depending on the soil characteristics, topography and climate of an area and their composition (Eldridge *et al*. 2000). The biotic crust also affects the microbiological characters of the soil e.g. the microfauna (Darby *et al*. 2010). As a major constituent of living ground cover in arid land environments, biological crusts may contribute up to 70% of this cover (Belnap *et al*. 2001, Barger *et al*. 2006). Disturbance or removal of these crusts could therefore have an important effect on the functioning of these ecosystems with the consequence of changes and the redistribution of nutrients and biota, which can be strong enough to affect plant growth.

Biological soil crusts form a physical barrier between the soil and the atmosphere. The heterogeneity in their ability to affect the infiltration of water and to retain particles and seeds results in the redistribution of materials in the ecosystem. The presence of crusts can have positive or negative effects on the establishment of seedlings depending on the plant species and the nature of the crust (Hawkes 2004, Facelli and Sringbett 2009). The entrapment of seeds and humidity due to the microtopography of crusts can increase germination (Eckert et al. 1986). There is also a possible phytotoxic effect on seeds and seedlings from the cyanobacteria (Codd 1995) and lichens in the crust (Harper and Marble 1988). The hydrological processes at the soil surface with crusts are complex and are poorly understood. Crusts can be hydrophobic (Eldridge *et al.* 2002) and their clearance has been shown to enhance infiltration in studies in the Negev desert in Israel, where the runoff of water from patches of crust into neighbouring vegetation was reduced (Eldridge *et al*. 2000). The presence of biological soil crusts can allow ponding of water on the soil surface (Barger *et al*. 2006). Numerous studies have shown that such ponding enhances infiltration and reduces erosion (Barger *et al*. 2006). The morphology of lichen and cyanobacteria species differentially enhance resistance to soil erosion, and so surface soil stability depends on the spatial distribution of the different types of crust (Aguilar *et al*. 2009). Belnap (2006) reviewed the current knowledge on the role of biological crusts on soil surface features and hydrological processes. It was found that biological crusts in hyper-arid regions reduce infiltration and increase runoff, have mixed effects in arid regions, and increase infiltration and reduce runoff in semi-arid cool and cold dry lands (Belnap 2006).

If the crust is broken, and a more heterogeneous surface produced, the composition of the vegetation can be influenced by the growth of some plant species increasing, while the growth of others may not be enhanced. This has been found with an increase in the growth of *Maireana pyramidata* in a semi-arid region, particularly if seeds were buried as a result from trampling, while *Atriplex vesicaria* had a smaller increase (Facelli and Springbett 2009). The species composition of the crust and plant species can interact, as the presence of lichen has been found to inhibit the germination of seeds and root penetration of two grass species, while mixed crust (assortment of lichens and mosses) did not have this affect (Deines *et al*. 2007). Consequently, they can affect the composition and distribution of the vegetation in the system.

Inorganic crusts, such as desert pavement, silt-clay (mechanical) crusts and chemical crusts, as well as the biological crusts, are highly vulnerable to the stresses generated under vehicle tyres (Wilshire 1983). Shear damage results in the destruction of the protective desert pavement, powdering the fine soil material and filling the cracks between surface polygons (Vollmer *et al*. 1976). Most research into soil surface characteristics in the semi-arid areas of

Australia have focussed on the effects of livestock grazing, and not on the effects of vehicles. Gradients in vegetation cover, species composition and soil properties develop around water sources due to grazing pressure creating a “piosphere” (Lange 1969). In these areas there can be a large amount of crust destruction. However, little is known about the impact where mineral exploration activities, such as those described in this study, result in long wide areas of continuous destruction of crust. In a system where there have been tracks cleared perpendicularly over sand dunes, the presence of crusts in the undisturbed area would have a stabilising effect on soil movement by reducing runoff and sediment and nutrient redistribution or loss.

There have been few studies conducted on AMF in Australian native ecosystems and none on the role of disturbance, particularly compaction, on the mycorrhizal status of these systems. In a study of plants in a semi-arid area of South Australia, McGee (1986) found that 30 annual species and 41 perennial species had AMF associations, and only four annuals and four perennials had no ectomycorrhizae or endomycorrhizae. Due to the role AMF associations have in the environment, research into their establishment and the species they interact with in natural ecosystems is of fundamental importance (Vierheilig *et al*. 1998).

AMF play a vital role in soil aggregation (Bethlenfalvay *et al*. 1999, Rillig and Mummey 2006). While this soil aggregation is important in agricultural systems, where it has been mostly studied, it is also of utmost importance in natural ecosystems (Vierheilig *et al*. 1998). This is particularly in the case of sand dune stabilization (Koske and Polson 1984). The hyphae of AMF aid in holding the soil together by the formation of aggregates. The quantification of the AMF present is important to know the extent of their role in this stabilisation process and to assess how their presence is affected by disturbance. Compaction has been found to have an effect on the growth of AMF and the amount of this influence is dependent on the AMF species (Drew *et al*. 2006). As different species of plants vary in their response to different AMF species, the species composition of AMF communities are one of the determinates of plant community structures (van der Heijden *et al*. 1998).

Moorman and Reeves (1979) conducted a study comparing the mycorrhizal content of the soil in a sagebrush community in Colorado and a county road, which was abandoned, ripped and left six years previously. In this study corn plants grown in the soil from the sagebrush community were 77% infected by mycorrhizae and those in the soil from the disturbed area were only 1% infected. There was a low source of inoculum in the disturbed soils as there was a low incidence of mycorrhizal plants growing. This supports the observations of Reeves *et al*. (1979) who inferred the slow regeneration of the vegetation could partially be due to the elimination or reduction in the number of viable propagules of mycorrhizal fungi. They found that 99% of the plant cover in the undisturbed area was mycorrhizal (vesicular-arbuscular), whereas in the disturbed area less than 1% was mycorrhizal. They concluded that the presence of the nonmycorrhizal species might hinder the succession of the plant community, as these species do not provide an adequate inoculum source for subsequent mycorrhizal species.

The aim of this chapter is to answer the following questions:

- Did the occurrence of disturbance affect the soil surface characteristics, and are there differences between topographical positions?
- Was there a difference in the occurrence and amount of AMF between the disturbed and undisturbed areas and was there a difference considering the topographic positions?
- Did the soil properties affected by disturbance change the infection potential of mycorrhizae?

Methods

The same scheme of sampling as described in Chapter 3 (Figure 3.2) was used to collect data from across the tracks and undisturbed site as well as along the tracks. Details of the location of tracks and how they were created are given in Chapter 2.

7.1 Soil Crust

Four 20 cm x 20 cm quadrats were placed so that there was one at each position across the tracks with five replicates at each 5 m section along the tracks. This resulted in 240 samples for the entire area. The soil surface was assessed and described as: no crust (soft, hard, loose or soft on top of hard), biological crust (presence of lichen and moss), physical (crust which crumbled easily when disturbed) and chemical (stain) in the disturbed and undisturbed areas along the tracks in September in spring 2005.

7.2 Mycorrhizae

7.2.1 Testing for mycorrhizae using molecular methods

Two 500 g soil samples were collected in autumn 2007 from each of the sections of swale, slope and crest from the three tracks and analysed by the Root Testing Service at South Australian Research Institute (SARDI) for mycorrhizal DNA. Five DNA tests were conducted, which covered various genera of arbuscular mycorrhizal fungi (AMF) as shown in Figure 7.1. The results were presented as Cycle threshold (Ct) values. This represented the PCR cycle number at which the fluorescent signal rose above a threshold. The data was presented this way because there was no 'DNA standard' for the AMF tests. Normally the fungus is cultured and a large amount of DNA extracted to make a standard and the Ct value can be converted to a value of DNA in DNA/g soil. While this is one of the future objectives of the Root Testing Service, the technique is not yet available. The data set for mycorrhizae with the most complete and reliable results using molecular methods came from only one group of AMF, Group A, which was the main *Glomus interadices* group (Figure 7.1). Ct values between 30 and 35 corresponded to significant levels of AMFs and some Ct values >40 were included even though possibly not as reliable for quantification.

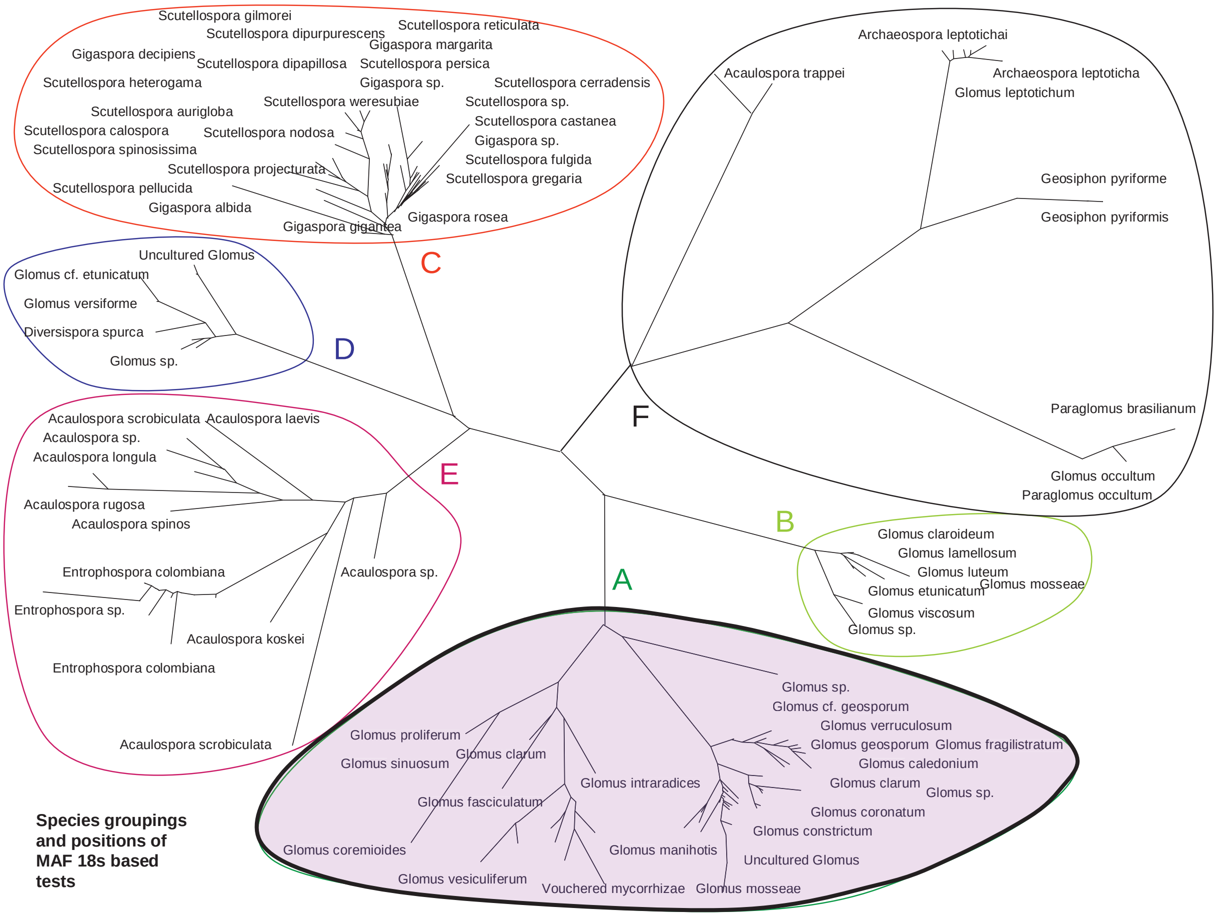

Figure 7.1 Groups of common AMF fungi – results from AMF group A used (shaded) – figure generated by Root Testing Service at South Australian Research Institute (SARDI)

7.2.2 Seedling and root testing for mycorrhizae

Intact soil cores were collected in March in autumn 2007 using a 10 cm diameter tube pushed into the ground to a depth of 10 cm. Cores were carefully removed so as to conserve the structure of the soil. Two cores were taken from the disturbed area in the wheel ruts and undisturbed areas from each of the swale, footslope, slope and crest along the three tracks resulting in 48 samples. These were placed in the glasshouse with three *Eucalyptus incrassata* Labill. seeds sown in one set of samples. Three *Medicago truncatula* (L. cv Jemalong) (barrel medic) seeds were sown in the other set samples a month later, as they are faster growing than *E. incrassata*. These species were chosen as *E. incrassata* is the dominant mallee eucalypt growing in the undisturbed areas off the tracks, while *M. truncatula* is known as a highly susceptible host for AMF. *E. incrassata* has been shown to have an association with ectomycorrhizae (Ashton 1976, McGee 1986) and endomycorrhizae (McGee 1986), however in this study only the endomycorrhizae were assessed.

Root samples were collected at 15, 22, 29 and 40 weeks after the seeds were planted at the end of autumn. This was done using an 8 x 1 cm^2 corer to retrieve soil cores containing roots from each tube with the *E. incrassata* seedlings growing in. The faster growing *M. truncatula* had cores taken after 6, 12, 18 and 28 weeks. The soil was washed from these cores and the root samples collected. The samples were placed in 50% ethanol (for preservation) and then cleared in 10% KOH solution. After a week they were washed in RO water and placed in 5% ink-vinegar solution with pure white household vinegar (5% acetic acid) and Schaeffer ink for another week (Vierheilig *et al*. 1998). Samples were then washed thoroughly in RO water and placed in 5% vinegar solution. The extent of AMF infection was determined by the grid intersection method (Giovannetti and Mosse 1980). The roots crossing the grid lines after the roots were dispersed above a grid of squares drawn on a petri dish, were observed under a dissection microscope at x 100 magnification and scored as positive for infection if there was any structure within the roots stained blue i.e. hyphae, vesicles or arbuscules. The percentages of infected roots were determined by counting all the roots intersecting the gridlines and the number infected. This method was adequate as there was consistency with only one person using it to assess all the samples. McGonigle *et al*. (1990) ascertained that most observers over or underestimated both proportions, and so relative levels of colonisation could be correctly detected across treatments by being consistent in this.

At the end point of the experiment after 28 weeks the roots were dried and weighed. For the above ground biomass plants were harvested after the last root cores were collected by cutting the plant off at surface level and weighed.

Statistical Analyses

For all the data sets JMPIN 4 (Copyright © 2010 SAS Institute Inc.) was used to test for normality and homogeneity of variances. The Shapiro-Wilks test was used to test for normality with $p<0.05$ indicating non normal data. Where the data were not normal a number of transformations were attempted, but none of them were effective and so analyses for non parametric data were carried out. Levene test (Levene 1960) was used to assess the homogeneity of variances in different samples with $p>0.05$ indicating homogeneity.

Where there were more than two factors, permutational multivariate analysis of variance PERMANOVA version 1.6 (as described in Chapter 3) was used and if there were two factors PerMANOVA (Anderson 2005) (as described in Chapter 3) was performed, and in these cases interactions between data sets assessed.

Where there was heterogeneity of variances a permutational analysis of multivariate dispersions (PERMDISP by M. J. Anderson) was used to assess this heterogeneity with a two-way ANOVA. Where this was significant the differences observed could be wholly or partially due to the dispersion of replicates.

To maintain the real level of significance at $p<0.05$ a Bonferroni correction was applied.

Soil Crusts

The data consisted of the number of quadrats at each position with each of the crust types of – no crust, biological crust, physical crust and chemical crust. The analysis was conducted using the number of quadrats scored according to the soil crust type. If there was more than one crust type in the same quadrat the score was from the one with the higher percent cover. The data sets were analysed using the three factors of across the tracks, along the tracks and crust to assess the differences between: the four soil surface features when nested within the positions across and along the tracks, between the positions along the tracks when nested within the positions across the tracks and between the positions across the tracks with the three tracks as replicates. This was repeated with the scores for biological crust and physical crust with the scores for no crust and chemical crust omitted.

The distribution of the data set was not normal for the crust characteristics and the variances were heterogeneous for across and along positions and tracks.

Mycorrhizae levels in the soil using molecular methods

The two replicate samples were averaged as there were some missing values, and so there were two factors of positions along the tracks and across the tracks with the three tracks as replicates.

The distribution of the data set was normal and the variances for positions along the tracks were homogeneous and heterogeneous for the positions across the tracks.

Biomass of *Eucalyptus incrassata* and *Medicago truncatula* seedlings

The *E. incrassata* and *M. truncatula* root weights and above ground biomass were averaged for each pot, and so there were the two factors of positions along the tracks and those across the tracks with the three tracks as replicates. It was considered that plant density was not high enough to result in intraspecific competition, which can be increased by mycorrhizal symbiosis, as there were 3 plants to a 10 cm pot (Facelli *et al*. 1999).

The distribution of the root weight data set was normal for the *E. incrassata* seedlings, but not for the *M. truncatula* seedlings and the variances were homogeneous for the data set from positions across and along the tracks for both.

The distribution of the above ground biomass data set was not normal for both species and the variances were homogeneous for the *E. incrassata* data set from positions across and along the tracks, and for the *M. truncatula* seedlings were homogeneous for the positions across the tracks and heterogeneous for the positions along the tracks.

Mycorrhizae percentage infection in *Eucalyptus incrassata* and *Medicago truncatula* roots

The data sets for mycorrhizal infection in *E. incrassata* and *M. truncatula* seedlings were analysed to assess the differences between the positions along the tracks and between the positions across the tracks with the three tracks as replicates. The data sets were also analysed for differences between the tracks using the three positions along the tracks as replicates.

The distribution of data for mycorrhizal infection in *E. incrassata* and *M. truncatula* seedlings, which consisted of the three factors of along, across and time was analysed to assess the differences between: the four scores over time (E1, E2, E3 and E4) when nested within the positions across the tracks and the positions along the tracks; between the positions across the tracks when nested within the positions along the tracks and between the positions along the tracks with the three tracks as replicates.

The percentage score for the infection was arcsine transformed.

Results

7.1 Soil crusts

There were more quadrats with no crust than with any type of crust (PERMANOVA version 1.6, $F_{48,191}$=13.44, p<0.01) (Figure 7.2).

There were more quadrats with a biological crust in the undisturbed area than the other positions across the tracks (PERMANOVA version 1.6, $F_{3,95}$=5.9, p<0.01), with the undisturbed area with more biological crust than the centre (t=2.83, p<0.01), the wheel rut (t=2.1, p<0.05) and the shoulder (t=2.34, p< 0.05) (Figure 7.3).

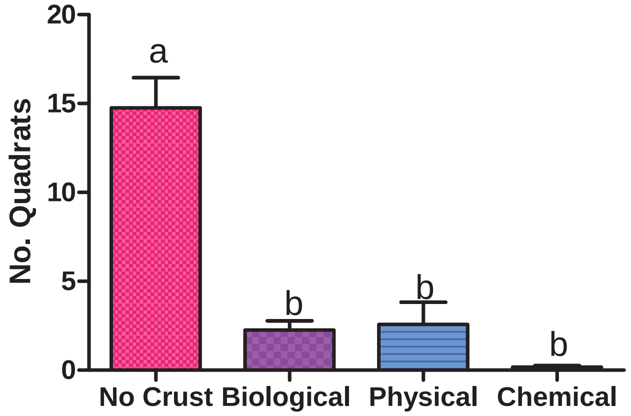

Figure 7.2 Differences between crust types of – no crust, biological crust, physical crust and chemical crust (±95% CI, n=4) (positions across and along the tracks combined) - letters denote differences at p<0.05 level

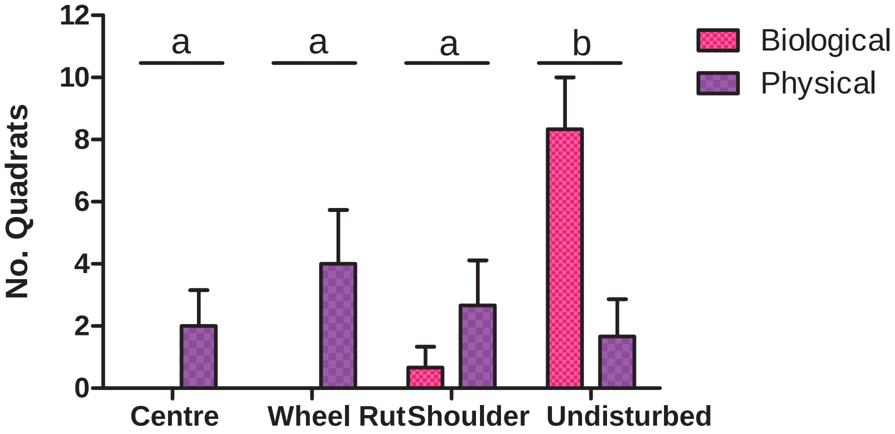

Figure 7.3 Differences between positions across the tracks in terms of the biological and physical crust (±95% CI, n=3) - letters denote differences at p<0.05 level

7.2 Mycorrhizae

7.2.1 Testing for Mycorrhizae using Molecular Methods

The two way ANOVA for the data set of AMF Group A in the soil for the positions along the tracks and between the disturbed and the undisturbed areas was not significant (Figure 7.4).

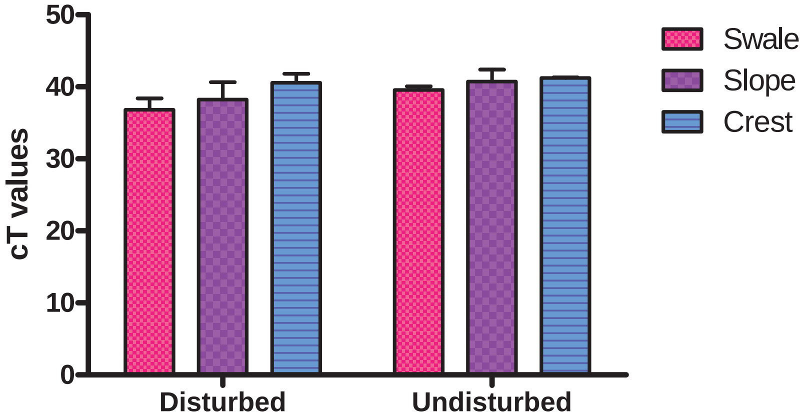

Figure 7.4 AMF (Group A) at positions across the tracks (disturbed and undisturbed) at the positions along the tracks (swale, slope and crest) (±95% CI, n = 3)

7.2.2 Seedling and root testing for mycorrhizae

There were no significant differences between the positions along and across the tracks using a PerMANOVA for *M. truncatula* below ground biomass, *E. incrassata* above ground biomass and *M. truncatula* above ground biomass.

There were no significant differences between the positions along the tracks using a two way ANOVA for *E. incrassata* below ground biomass and none in AMF infection between the positions along and across the tracks for *E. incrassata* roots and for *M. truncatula* roots (Figure 7.5).

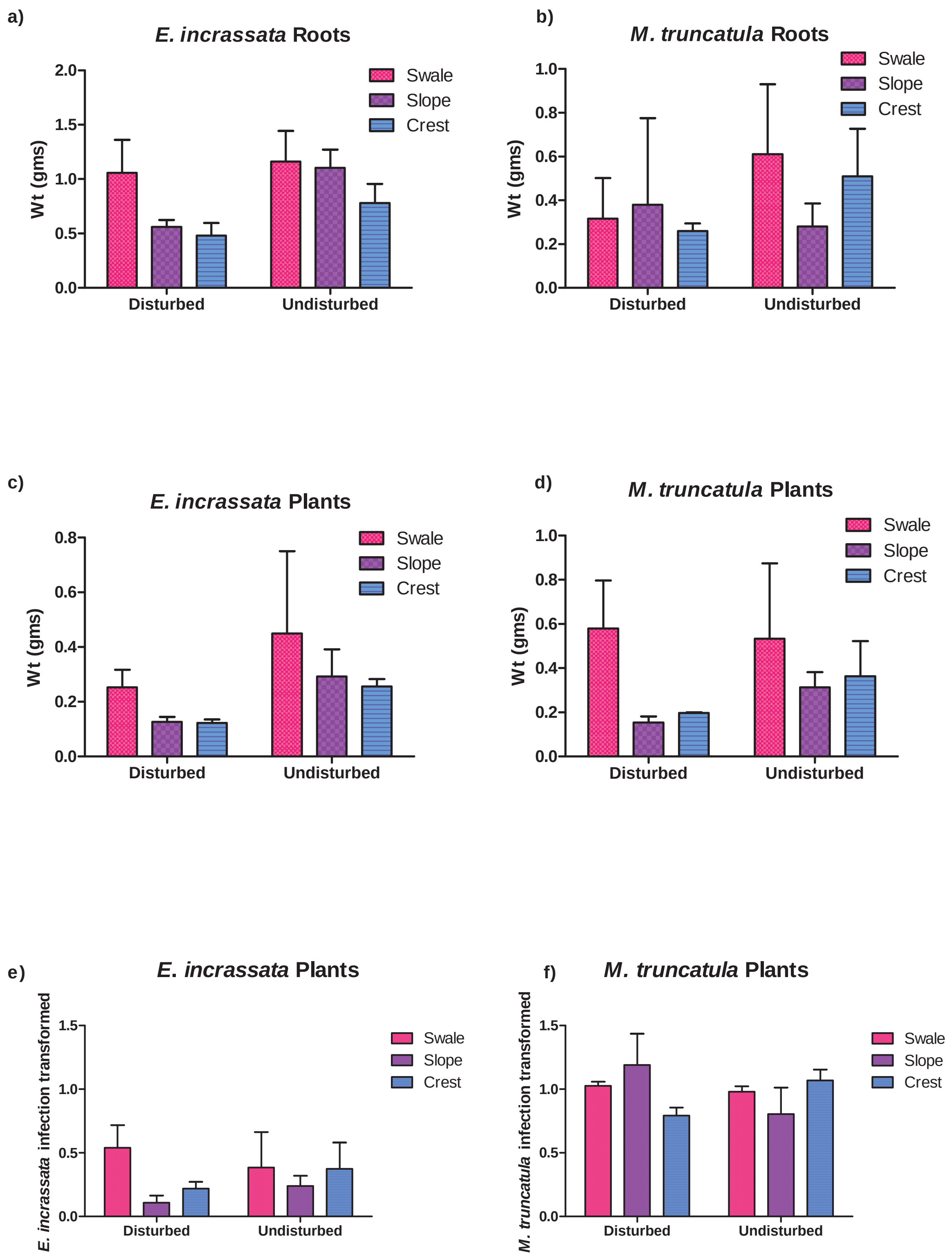

Figure 7.5 a), c) and e) *E. incrassata* and b), d) and f) *M. truncatula* below and above ground biomass and % Mycorrhizal infection (±95% CI, n = 3)

Mycorrhizae percentage in *E. incrassata* roots over a 40 weeks period

There were no significant differences between any of the positions across or along the tracks or between the scores over time for the amount of mycorrhizal infection of the *E. incrassata* roots (Figure 7.6).

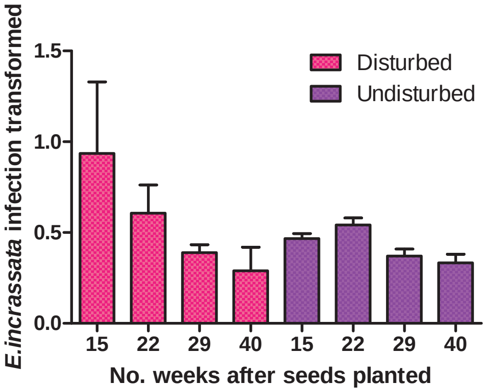

Figure 7.6 Mycorrhizae percentage in *E. incrassata* roots over time from four sampling times (15, 22, 29 and 40 weeks) (±95% CI, n = 3)

Mycorrhizae percentage in *M. truncatula* roots over a 28 week period

There were significant differences (PERMANOVA version 1.6, $F_{2,71}$=5.05, $p<0.05$) between the scores for positions along the tracks with the *M. truncatula* roots from the soils from the slope having more infection than the crest (t=2.39, $p<0.05$), (Figure 7.7a)). There were also differences over time (PERMANOVA version 1.6, $F_{18,71}$=3.67, $p<0.01$) for the amount of mycorrhizal infection of the *M. truncatula* roots (Figure 7.7b)).

a) **b)**

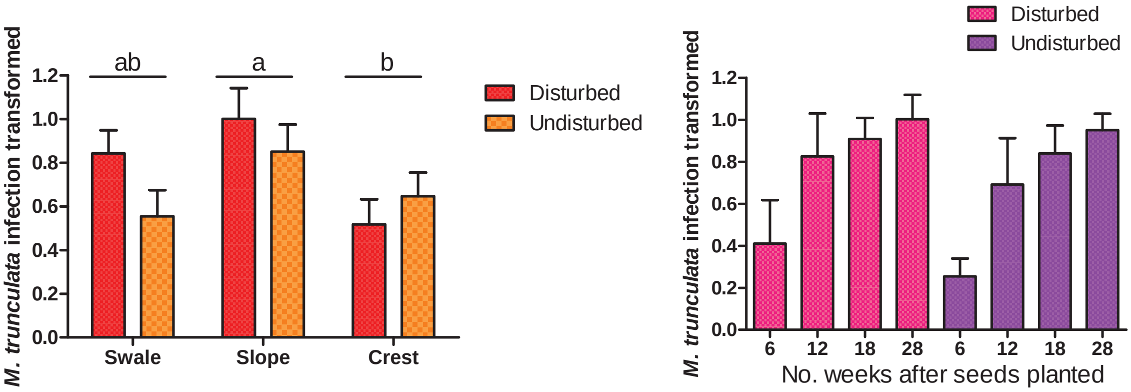

Figure 7.7 Mycorrhizae percentage in *M. truncatula* roots (±95% CI, n = 3) a) Along the tracks (swale, slope and crest - letters denote differences at p<0.05 level and b) Over time from four sampling times (15, 22, 29 and 40 weeks)

Discussion

The soil surface in both the disturbed and the undisturbed areas was mainly bare with no crust. In the undisturbed area, the most prevalent type of crust was biological, while the positions on the tracks had more physical crust. The undisturbed area had about eight times the amount of biological crust as the disturbed area. As seen previously (Chapter 3), there appeared to be more soil infiltration capacity in the undisturbed area, possibly due to less compaction and this resulted in less erosion. The combined impact of biological crust loss and compaction has the potential to exacerbate the intensity of this erosion. The roughness of the soil surface is an important characteristic. The presence of biological soil crusts allows more ponding of water on the soil surface and enhances infiltration and reduces erosion (Barger *et al*. 2006), therefore, there may be less sediment bound nutrient movement in the undisturbed area than along the tracks (Chapters 3 and 4). There was a possibility that the biological crust in the undisturbed area consisted mainly of late successional species, as there was no evidence of anthropegenic disturbance. If the crust consisted of later successional species, the future succession of growth is likely to result in less stabilising, early successional cyanobacterial crusts (Belnap 1996). As regeneration of the crust to the late successional stage of cyanolichens may take decades to centuries, there may also be a large loss of nutrients to the ecosystem (Barger *et al*. 2006). A more thorough study to look at the distribution and identification of different types of crust would enable a better understanding of their ecological roles. This study has shown that the destruction of the biological crust on the tracks has resulted in a higher amount of physical crust. This type of crust, along with higher compaction and less water infiltration, was a possible causative factor in the higher erosion observed in the disturbed area. Over time, with less nitrogen fixation occurring due to this destruction of biological crusts on the tracks the nutrient status of the soil would also change.

There were no differences in mycorrhizal infection between the disturbed and undisturbed areas for both *E. incrassata* and *M. truncatula*. One possible reason for this could be due to the extension of the mycorrhizal hyphal network from the adjacent vegetation into the disturbed area, as this is an important dispersal mechanism for AMF (Scheltema *et al*. 1985). There could also be retention of hyphae and spores in the soil over time since the vegetation was cleared. If the tracks were wider then there would be a possible difference as there would be a threshold on distance to vegetation for mycorrhizae to exist in the soil. The composition of the vegetation in the undisturbed area adjacent to the track would also have an influence, as plant species are one of the determinants of the AMF species present (Brundrett 1991). Little is known about the spatial component of mycorrhizal ecology. This is an important and novel area of research, as the size of the disturbance is possibly related to the presence of mycorrhizae within the disturbance. There were no significant differences in AMF group A content in the soil between the disturbed and undisturbed areas, or the topographic positions. The above and below ground biomass for both *E. incrassata* and *M. truncatula* also showed no significant differences reflecting the lack of differences in AMF infection.

The amount of mycorrhizal infection for the four root samples collected over time for *M. truncatula* roots showed that the slope had more infection than the crest and that there was a significant increase in infection over time. These differences were not apparent with *E. incrassata.* As AMF spores and hyphae are mainly in the top 15 to 25 cm. of soil (Kabir 2005) any movement of this soil due to erosion could result in changes to the AMF content (da Silva *et al.* 2005). The elevated infection in the *M. truncatula* plants in the soil from the slope could possibly be due to soil movement (Chapter 2). However, this was similar in both disturbed and undisturbed areas. Alternatively, the elevated infection could be due to the different conditions of the soil (water, nutrients) in this position. The plant species growing in the undisturbed area of the slope could also have an influence (Brundrett 1991).

There have been few studies in Australian systems on the mechanisms of the mycorrhizal infection of native vegetation as most studies have been conducted in an agricultural setting. The infection of mycorrhizae observed in this study could possibly be more likely due to hyphae than to spores, as McGee (1989) found that there were low spore numbers in the soil in a system of *E. incrassata* growing over *M. uncinata* on siliceous sands in South Australia. McGee *et al*. (1997) in their study on agricultural clay soil used to grow cotton found that the hyphal network was an important source of infection and that the low proportion of spore initiated AMF was due to low viability, and not due to dormancy. Jasper *et al*. (1989) found that the separation of hyphae from the roots of the host plant did not reduce the viability of the hyphae. With the movement of soil down the slope, a resultant build up of AMF propagules in the swale would be expected, which was not the case. Therefore, conditions were more conducive for the persistence of mycorrhizae in the slope compared to the swale. Jasper et al (1989) found the destruction of the integrity of the hyphal network to be the cause of a reduction of AMF infection in glasshouse experiments. As the inoculum in the soil in the disturbed and undisturbed areas is most likely to be hyphal (McGee 1989), the soil movement during large summer rainfall events in 2007 down the slopes could have gradually destroyed the AMF hyphal network so there was a higher infection on the slope and less in the swale. Therefore, the soil in the swale possibly contained hyphal networks that were no longer intact and not viable. The reduction in soil stabilising mycorrhizal hyphae at the crest would heighten this movement of soil.

Compaction is another soil characteristic that could explain the reduced infection in the plants in the swale soil. There have been few studies on the impact of compaction on mycorrhizae in natural ecosystems. Entry *et al*. (1996) found the amount of infection of maize roots and root biomass in sites treated with compaction and no tillage was significantly less than those with no treatments. Soil compaction, which was higher in the swale (Chapter 3), results in smaller pore sizes and this can prevent the growth of hyphae through the soil resulting in a negative impact on the AMF population (Drew *et al*. 2006). Rathore and Singh (1995) also found that there was a significant negative correlation between the size of the AMF population and soil clay content, which in this study was greater in the swale soil (Chapter 3).

The mycorrhizal infection in the soil in which the *M. truncatula* plants grew, initially had higher levels in the disturbed soils than in the undisturbed soils. The level of infection increased significantly over 28 weeks in both disturbed and undisturbed soils. This may be an indication of more ruderal fungi in the disturbed soils. Under disturbance you would expect mycorrhizal fungi that produce more spores to rely less on hyphae, and so they may be able to infect faster. By the last reading the levels were the same and approaching maximum infection, while the *E. incrassata* showed no significant differences in growth over time. The mycorrhizal component of the ecosystem can be a determining factor in which plant species grow in a system. When soil is compacted a fungus that can find a new host would be more likely to thrive (Drew *et al*. 2006). Hence, the composition of the mycorrhizal population could change, and along with this plant species that could regenerate would be affected.

In the seedbank study and annual seedling survey there was more growth in the swale than the other positions along the tracks and this difference was larger on the tracks than in the undisturbed area (Chapter 5). The mycorrhizal infection did not show the same difference and there were lower AMF levels in the swale. *Calandrinia* spp. and *Crassula* *colorata* were the main species contributing to the elevated number of seedlings in the swale from the seedbank study and these are non mycorrhizal (Dhillion *et al*. 1995). In terms of the potential for weed invasion this study has shown more growth of the nonmycorrhizal species *Carrichtera annua* in the swale soils than the crest soils, reflecting the same pattern as native *Calandrinia* sp and *Crassula colorata* (Chapter 6). This could indicate a competitive advantage of nonmycorrhizal species, and any antagonistic influence of mycorrhizae on the growth of these species appeared to be negligible. This is definitely an area that needs further investigation. The presence of mycorrhizae, therefore, may or may not facilitate some invasive species or conversely may confer a competitive advantage to native species, e.g. a weed that does not require AMF can be disadvantaged when AMF are present, but advantaged when there is not any (Reinhart and Callaway 2006).

This study shows that disturbance reduced the biological crust on the tracks, but did not affect the distribution of AMF, which appeared to be slightly affected by topography. As the crust stabilises soil, its reduction on the tracks was likely to add to the erosion potential. The redistribution of AMF propagules could be due to physical processes, such as erosion and compaction, and not due to the lack of vegetation on the tracks. There is a probability of changes to the AMF in the soil in the disturbed area increasing compared to the undisturbed area over time if the amount of erosion and compaction increases. There is a likelihood of this occurring if there is little or no regeneration of vegetation.

§

Chapter 8 Conclusion

Summary

In the disturbed area there was more erosion (mainly Track 2), compaction, bulk density, soil water, total N, pH, conductivity, carbon, emergent seedbank, annual seedlings, % cover annuals and weed invasibility (Table 8.1). In the undisturbed area there was more potassium, litter, ant activity, number of seedlings in the litter quadrats and number of seedlings where there was no litter, *Eucalyptus incrassata* – caged and uncaged, possibly mycorrhizae, *E. incrassata* and *Medicago truncatula* above ground biomass and below ground biomass (Table 8.1).

Table 8.1 Numbers denoting the level of impact with 4 being the highest impact to 1 being the lowest (* p<0.05, **p<0.01, ***p<0.001)

	Centre	Wheel Rut	Shoulder	Undisturbed
Compaction (kgf – 4 highest)	3**	4***	2	1
Erosion (amt. soil movement – 4 highest)	4**	4**	4**	1**
Bulk Density (μgm/cm^3) (4 highest)	1**	4**	1**	1**
Soil Water - Soil Samples (% water by weight) (4 highest)	3	4	2	1
Soil Water - Moisture Meters (m^3/m^3) (4 highest)	2	4	3	1
Litter (amt. of cover – 4 highest)	2**	1**	3*	4*
Potential for weed invasion (gm) (biomass of C. annua)	3*	4*	2	1
Biological Crust (no. quadrats with crust) (4 highest)	1**	1**	3**	4**
Total Nitrogen (%) (4 highest)	4	3	2	1
Emergent Seedbank No. Seedlings 2006 (4 highest)	4	2	3	1
Emergent Seedbank No. Species 2006	4	1	3	2
Emergent Seedbank No. Seedlings 2007	2	3	4	1
Emergent Seedbank No. Species 2007	3	4	2	1
Emergent Seedbank No. Seedlings 2007 smoke	4	2	3	1
Total Carbon (%) (4 highest)	1	4	3	2
pH (4 – highest)	3	4*	1*	2
Conductivity (μSiemens) (4 highest)	4	1	3	2
Potassium (mg/kg) (4 highest)	2*	1	4*	3
Ants - No. Seeds Removed (more gone in Dist. than in Undist.)	3	3	3	4
No. Species Annuals in the Field (4 – highest)	4***	3	2	1
% Cover Annuals in the Field (4 – highest)	4***	3	1	2
No. Seedlings with Litter (more in the Undist. than in the Dist.)	1	1	1	4
No. Seedlings without Litter (more in the Undist. than in the Dist.)	1	1	1	4
Growth *E. incrassata* Seedlings in Field (gm) (4 – highest)	1	1	1	4
Growth *E. incrassata* Seedlings Caged in Field (gm)	1	1	1	4
Growth *E. incrassata* Seedlings Uncaged in Field (gm)	1	1	1	4
Mycorrhizae in Roots (%) (more in the Undist. than in the Dist.)	1	1	1	4
E. incrassata above ground Biomass (gm) in Mycorrhizae Exp.	1	1	1	4
E. incrassata below ground Biomass (gm) in Mycorrhizae Exp.	1	1	1	4
Medic above ground Biomass (gm) in Mycorrhizae Exp.	1	1	1	4
Medic below ground Biomass (gm) in Mycorrhizae Exp.	1	1	1	4
AMF Species Group a (4 – highest amount)	1	1	1	4

The main environmental impacts documented here, namely soil compaction and subsequent changes in infiltration and erosion (Table 8.1, Figure 8.1), occurred after clearing the vegetation and with the use of the tracks. The frequent passes by a number of vehicles over a relatively short period of time seemingly resulted in changes to the transport processes of water, soil, nutrients and seeds. With greater compaction on the tracks water dynamics were changed and the subsequent decrease in infiltration would lead to less accessibility of water for plant growth. The occurrence of erosion along the tracks was promoted by the synergistic effects of removal of vegetation and their root systems, a decrease in litter deposition, reduced biological crust cover and lower mycorrhizal infective capacity at the crest and soil compaction (Figure 8.1). The subsequent increase in soil erosion would further reduce the potential for regeneration. The dunal topography and soil types of the area play an important role in the type of impacts. Soil properties, particularly clay content, influenced the compaction. The depth of the most compacted layer was thus affected, with sandier soil having a deeper zone of compaction. The strongest compaction was found in the wheel ruts enabling water to move faster down the tracks than in the undisturbed area, and so picking up soil, nutrients, seeds and vegetative fragments, including root fragments and associated mycorrhizae (Koske and Gemma 1990). This transport possibly resulted in higher concentrations of these components in the low lying swale. More seedlings and species emerged from the seedbank in the swale on the tracks and these processes probably contributed to this (Figure 8.1). This was reflected in the number of species and percent cover of annual seedlings in the field. These annuals also showed a greater growth on the more exposed centre of the tracks than in the undisturbed area. Compaction was not as great in this position as in the wheel ruts, and so this did not have as much effect. The consequence of more annuals germinating in the possibly higher temperatures in the centre of the tracks could be that if there is an increase in temperature and less rainfall, as in a drought, the seedbank would become depleted if these species are unable to set seed for future generations (Figure 8.1). This is of particular importance in that the annual community contributes substantially to the biodiversity of the vegetation.

Weed species are known to invade disturbed areas, because they are adapted to withstand the stresses in such environments (Hobbs and Humphries 1995). The potential for invasion as assessed by the phytoassay using *Carrichtera annua*, a common weed in nearby agricultural areas, indicated that some soils of the disturbed area were more conducive to their growth (Table 8.1). The continued influence on the tracks of soil compaction would affect the system reinforcing and producing more degradation, and so increase the possibility of invasion of weeds. The swale on the tracks was identified as the most likely site for weed establishment as the deposition of nutrient rich material can encourage growth of species requiring disturbance and/or nutrient enrichment (Hobbs and Atkins 1988) (Figure 8.1). The disruption of the canopy increases exposure, which can also encourage weed growth. Very few weeds were observed from the soil seedbank emergence analysis and observations in the field. This absence of weeds at the site was most likely due to the lack of propagules. This was unexpected, particularly with the amount of traffic occurring in the exploration process. Even with the extremely low nutrient status of the soil possibly limiting weed growth it is important to prevent the introduction of seeds through restricting vehicle access. Continuous monitoring of the area should be conducted with a focus on the swales since they are the most likely sites for invasion as they have the highest soil resource availability (Figure 8.1). More thorough investigation of the soil seedbank using seed extraction methods could possibly disclose the presence of seeds of invasive species that have not had the right conditions to germinate and become established. Long term monitoring including similar studies to the present one conducted in the field at different times of the year over a number of years would give invaluable information on the successional processes in relation to the species present and rainfall patterns. The results could then be used to predict the potential of regeneration of vegetation in the disturbed area when no remediation has taken place.

This study began a year after the last use of the access tracks that were cleared for mineral exploration. At the time there was very little regeneration on the tracks, with the exception of some resprouts from perennial lignotubers. *Eucalyptus* sp. and *Melaleuca uncinata* had resprouted in the less compacted areas after a relatively short time. The few other perennial plants that managed to grow were shown to have a low survival rate. Those species of the perennial vegetation that were obligate reseeders and those with slow reproductive cycles were less likely to become established on the tracks.

Young perennial plants, which as adults have extended root systems with access to moisture in the deeper layers, may die before their roots are long enough to access this water. As Pate (1994) pointed out, Proteaceae species reach the main water table 2.3 m below the surface in their first season through a single taproot. If this root cannot penetrate the first 5 cm. of soil, which could be the case in severely compacted soil, the plant would die. As

Smith *et al.* (2001) showed a 60% reduction in root growth of four Australian tree species at 1.5 MPa, there is a possibility of soil compaction causing a restriction in growth where compaction exceeds this. This was the case in the wheel rut in the swale at the depth 0 – 3 cm and there was substantial increase to 3.92 MPa in the 6 – 15 cm range. Apart from the physical and chemical restrictions to root growth caused by a lack of interstitial spaces in the soil and lack of oxygen, there would be a restriction to water infiltration resulting in a dry zone below the compacted layer. Annuals and many perennial monocots have a shallow root zone and can possibly take advantage of the moisture held in the top five centimetres soil, however this zone would dry out very quickly after rain. Regeneration of perennial vegetation on the tracks consisted initially of equal numbers of monocot and dicot plants along the slope, but after 28 weeks there were many more dicot plants with lignotubers and deeper roots than shallow rooted monocots growing. *Triodia* spp., which was one of the primary plants in the area, was unable to regenerate on the tracks, even though seedlings established, they did not survive to maturity. The lack of survival was most likely due to restricted root growth from the lack of water in the deeper layers of the soil resulting from soil compaction. As there was also erosion they were possibly dislodged with the movement of soil down the tracks. Given the requirement of the genus for mycorrhizae, changes in fungal infectivity could have been involved, but this was less likely.

Overall, the functioning of the ecosystem is changed in the vicinity of the linear disturbance of these access tracks (Figure 8.1). This has resulted in conditions unfavourable for the regrowth of perennial vegetation in the disturbed area. The impacts appear to be confined to the area actually cleared with little or no edge effects. However, further studies are needed to determine the likelihood of the subsequent expansion of the initial area of disturbance.

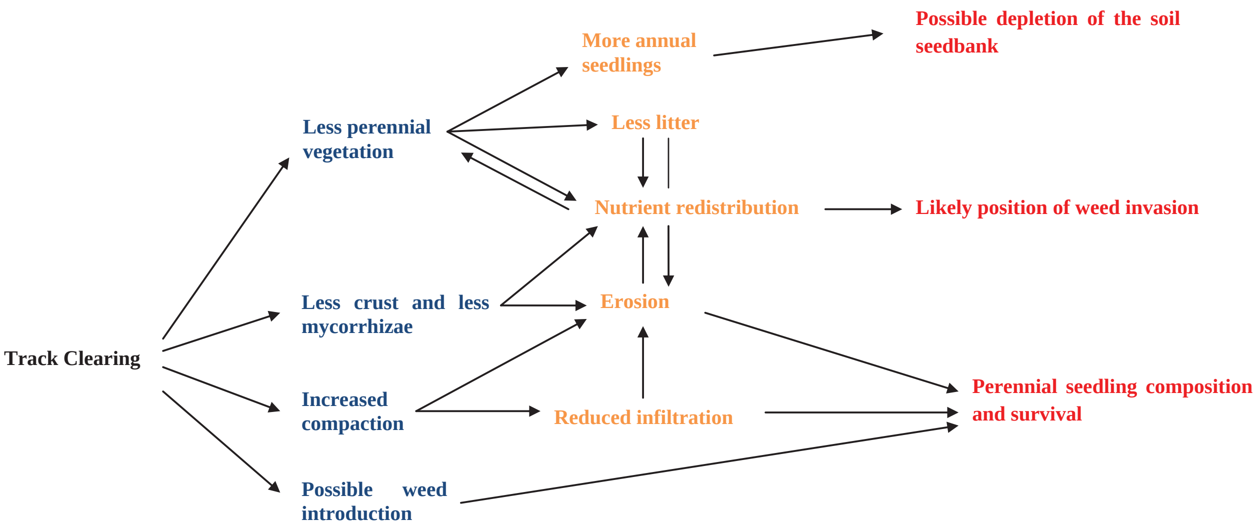

Figure 8.1 Summary of the processes and interactions in the ecosystem that have been altered by the clearing of access tracks

Future Impacts

Disturbance can play either a positive role in enabling greater diversity in an ecosystem, or a negative role, and there are all the gradations in between these two extremes (Hobbs 1987). Disturbance effects change over time. As Halpern and Spies (1995) explained, there are initial, direct and subsequent effects of disturbance. It is important to investigate disturbance regimes in this light, particularly in already fragmented natural ecosystems (Hobbs 1987). As has been shown in this study one of the main impacts of clearing land was accelerated soil erosion and continued landscape degradation can be a consequence of this (Noble and Bradstock 1989). Soil can be lost to parts of the system and the formation of new soil could take hundreds or even thousands of years (Kockelman 1983). This is particularly the case in a low productivity system where most of the nutrients concentrate in the small amount of organic matter in the top soil. Given the low productivity and slow decomposition rates in these areas organic matter would accumulate very slowly.

Assessing the changes that have already occurred since the clearance of the tracks using satellite imagery from previous successive years, along with mapping the data collected in this study using ArcGIS, would give a scenario of the possible expansion of the initial impacts to the area. However, due to time limitations this was not done in this study. Studies have been conducted in areas of the Mojave Desert, which have been severely disturbed by military and recreation vehicle usage resulting in the soils becoming extremely compacted (Webb 2002). Webb (2002) used a linear model and found that recovery of the soil and vegetation would require a century, with the 0-6 cm depth taking 92 – 124 years, and that this recovery would be significantly related to elevation. The use of off road vehicles is increasing rapidly, particularly as people want to explore undeveloped areas as the population is becoming more urban. The impacts of this type of perturbation of natural environments are increased as people tend to take the same route through difficult to traverse countryside (McIntyre and Lavorel 2007). Wherever tracks have been cleared there is an increased chance of these being used by recreational vehicles to access areas of natural vegetation. Measures can be taken to cover the entrances from public roads on to these tracks, but with technology such as Google Earth$^{(TM)}$ their whereabouts are obvious and people can drive around any obstruction.

Fire is an important variable that was not addressed in this study. Fire is indeed a significant ecological factor of semi-arid ecosystems, such as Pinkawillinie CP. A possibility that could be further considered would be to create an experimental fire over the area of disturbance studied to assess the impact on the regeneration of the vegetation along the tracks. A fire would redistribute nutrients and reproductive propagules. The burning of vegetation produces ash rich in all nutrients except nitrogen (Pate 1994), and as the tracks are narrow and have close contact with the surrounding vegetation it would be expected that this ash would fall on the tracks. This, along with seeds being liberated from species requiring fire, would potentially produce growth on the tracks. However, a fire would not affect compaction and the related reduced infiltration, and so the negative effects of this would still impact on the subsequent growth. This could be alleviated by scarifying or ripping the compacted soil. This is another area that requires more research as different soil types would need different treatments.

The added effect of climate change also needs to be considered as this will have an impact on environments already stressed by disturbance. The report on the Impact of Climate Change in South Australia undertaken by CSIRO Atmospheric Research uses the scenarios produced from computer modelling. This has determined some of the projected impacts for the northern pastoral area of the Eyre Peninsula region, the border of which goes through the middle of Pinkawillinie CP (McInnes *et al.* 2003). If there are no policies to reduce emissions, temperatures in this region are predicted rise by 0.4^0C - 1.6^0C by 2030 and 1.1^0C - 4.9^0C by 2070. The rainfall is predicted to either be reduced by 8% or stay the same by 2030 and reduced by 25% or stay the same by 2070 (McInnes *et al*. 2003). There is also the prediction for the period from 2051 to 2090 of heavier rainfall events between November and April (i.e. summer) over the north of South Australia with a 20% increase in frequency of events (McInnes *et al*. 2003). As has been shown in my study there was a large amount of soil movement in the heavy summer rains of 2007 after a drought through the winter of 2006. If the intensity and frequency of summer and autumn rainfall events increases there is the likelihood of increases in erosion in these disturbed areas.

The rate of wetting and drying affects the amelioration of compaction due to clay-mineral expansion and contraction. In areas with winter rains there is a lower frequency of wetting and drying and slower recovery of compacted areas, while areas with summer rains would have more frequent cycles and recover faster (Webb 2002). Hence any changes in the climate moving towards summer rainfall, while increasing the likelihood of erosion also may increase the recovery time of compacted soils. The topography is also a factor as wetting/drying cycles increase with elevation (Webb 2002). If there is an increase in runoff and sediment loss there would be a resultant increase in carbon and nitrogen losses (Barger *et al*. 2006). Climate change may also affect the species composition of the important biological crusts with increased summer rain and increased temperature reducing the cover of late succession species (Belnap *et al*. 2004). A possible decrease in lichen cover could result in blue green algae increasing as they are much more resistant to high temperatures, as long as there is some moisture, and these do not stabilise the soils as well as lichen (Rogers 1989). It is important to restore landscapes towards their original state and manage them for sustainability to add to their resilience to climate change (Hilbert *et al*. 2007).

The growth of annual plants was higher on the tracks, but even if this was a continuing phenomenon the growth would never be vigorous enough to alter the compacted conditions, and so the infiltration of water to enable the establishment of deeper rooted perennial plants. As compaction and lack of water infiltration are the major impacts, the regeneration process is unlikely to follow the facilitation model (Connell and Slatyer 1977). Either the tolerance or inhibition models (Connell and Slatyer 1977) are more likely to be those in play. The perennial plants surviving on the tracks were of those species that can grow from lignotubers and those that have deep roots that can penetrate the soil. These species have mechanisms to tolerate the changed conditions on the tracks. Overall, there was very little growth of vegetation on the tracks. As few species appeared to tolerate the changes in compaction and water dynamics the chances of changes to the physical environment to enable the growth of less tolerant species would be limited. Therefore, to mitigate the impacts of the clearance of mineral exploration tracks some remediation would be required to enable adequate regeneration to take place. The quantitative information from this study should provide valuable information on the most important impacts to be ameliorated for the best likelihood of rehabilitation.

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Appendix 1
Baggy Green Tenement (Figure 2.6)

Coordinates AGD 84 datum; Western boundary 544800 mE

Eastern boundary 548250 mE

Southern boundary 6361000 mN

Northern boundary 6366000 mN (Adelaide Resources 10)

The length, aspect and elevation of each of the sections of slope of the three tracks studied:

Track 1 – 92 metres long, west facing, altitude 131 m to 134.7 m – 3.7 m (Figure 2.7)

Track 2 – 61 metres long, west facing, altitude 122.2 m to 139.9 m – 17.7 m (Figure 2.8)

Track 3 – 63 metres long, south east facing, altitude 111.3 m to 118.6 m – 7.3 m (Figure 2.9)

Appendix 2
Description of the number, type, age and extent of tracks cleared in Pinkawillinie CP

MINING COMPANY	**POSITION**	**DATE**	**METHOD OF CLEARANCE**	**NO KM**
SADEX	On Paney Road	1971	None – on side of existing road	
Carpentaria Exploration	On Paney Road	1971	None – on side of existing road	
Stockdale	WUD2 North	1986	Bulldozer with the blade down	
CRA Exploration Pty Ltd	Wudinna (WUD1)	1987	Bulldozer with the blade down on tracks outside of the park	28 km
Western Mining Company	Empire Prospect WUD9	1991		13.2 km
Western Mining Company	Dragon, Monitor, Skink Prospects (WUDNITBENICE)	1994	Bulldozer with blade raised and towing a concrete roller	37.2 km
ARL	Baggy Green WUD6	1999	Bulldozer with blade raised and towing a concrete roller for all prospects	82 line km Total over all prospects
ARL	WUDNITBENICE	2004		
ARL	WUD9	2003		
ARL	WUD2 central	1999 2003		
ARL	WUD1	2003		
ARL	COR11	1999		
ARl	Schwerdt’s	2004		

Appendix 3

Perennial Vegetation Species List, Plant Number, Seed Characteristics and Methods of Dispersal

Family	Species	Total	Seed Characteristics and Methods of Dispersal
Poaceae	*Triodia scariosa (irritans)*	84	Wind, fire
Poaceae	*Triodia lanata*	69	Wind, fire
Myrtaceae	*Babingtonia behrii*	65	Seeds without endosperm, angular
Myrtaceae	*Leptospermum coriaceum*	43	Fire, seeds ± ovoid,~ 0.5mm, reticulate and occasionally ridged or winged, or irregularly linear and striate
Myrtaceae	*Melaleuca uncinata*	38	Fire, seeds without endosperm or endosperm sparse and thin; testa thin and lignotuber propagation
Cupressaceae	*Callitris verrucosa*	25	Fire, Winged, wind
Cyperaceae	*Lepidosperma laterale*	22	Myrmecochorous, hemicryptophyte, buds at or near the soil surface, nut ovoid, 2.5–4 mm long1.3–2.0 mm diam.,pale to dark brown,
Epacridaceae	*Leucopogon cordifolius*	21	Myrmechorous
Phormiaceae	*Dianella revoluta*	17	Fleshy fruit, hemicryptophyte, vertebrate
Polygalaceae	*Comesperma scoparium*	17	Myrmechorous - seeds are flattened-ellipsoid, c. 3 mm long, pubescent, with a linear, membranous basal appendage c. 2 mm
Myrtaceae	*Calytrix involucrata*	14	Seeds without endosperm or endosperm sparse and thin; testa cartilaginous or thinly membranous
Myoporaceae	*Eremophila scoparia*	12	Fruits are dry with a papery exocarp or drupaceous with a fleshy or succulent mesocarp and a woody or crustaceous endocarp
Proteaceae	*Grevillea ilicifolia var lobata*	11	Winged, endosperm absent
Myrtaceae	*Eucalyptus socialis*	8	Fire, wind
Rhamnaceae	*Cryptandra amara var amara*	6	Myrmechorous - seeds with thin, oily albumen, sometimes exalbuminous; embryo large, oily, straight or rarely bent.
Fabaceae	*Acacia calamifolia*	6	Myrmechorous, seeds large, with a filiform funicle or fleshy aril
Papilionaceae	*Dillwynia uncinata*	3	Myrmechorous - seeds often have a hard coat
Lamiaceae	*Westringia rigida*	3	Seeds with or without endosperm
Myrtaceae	*Calytrix tetragonia*	3	Seeds without endosperm or endosperm sparse and thin; testa cartilaginous or thinly membranous
Fabaceae	*Acacia ancistrophylla var lissophylla*	3	Myrmechorous - seeds large, with a filiform funicle or fleshy aril, and sometimes bear a u-shaped line called a pleurogram
Fabaceae	*Acacia spinescens*	2	Seeds longitudinal, oblong-elliptic; aril clavate
Casuarinaceae	*Allocasuarina muelleriana*	2	Fire, Wind
Dilleniaceeae	*Hibbertia riparia*	2	Myrmechorous - seeds 1 to numerous; endosperm copious , oily
Caesalpiniaceae	*Senna nemophylla var zygophylla*	2	Seeds with u-shaped line (pleurogram) usually lacking.
Myrtaceae	*Eucalyptus incrassata*	2	Fire, wind
Epacridaceae	*Astroloma conostephioides*	1	
Rhamnaceae	*Cryptandra leucophracta*	1	
Boraginaceaea	*Halgania andromedifolia*	1	Seeds vertical or oblique , coat membranous

Appendix 4

Differences in the perennial plant species between positions along the tracks - Indicator species analysis

	Section (max)	**p**
Calytrix involucrata	Crest	0.3389
Melaleuca uncinata	Crest	0.3677
Cryptandra amara var amara	Crest	0.5067
Comesperma scoperia	Footslope	0.5545
Leptospermum coriaceum	Crest	0.5613
Lepidosperma lateralis	Slope	0.5637
Dianella revoluta	Footslope	0.6723
Triodia scariosa	Crest	0.7856
Triodia lanata	Crest	0.9748
Babingtonia behrii	Swale	1
Callitris verrucosa	Slope	1
Leucopogon cordifolius	Swale	1
Eremophila scoparia	Slope	1
Eucalyptus socialis	Footslope	1

Appendix 5

Differences in the perennial plant species in terms of dispersion methods between positions along the tracks – Indicator species analysis

	Section (max)	p
Wind	Swale	0.1758
Wind/Fire	Crest	0.3439
Fire	Crest	0.6317
Ants	Slope	0.7059
Unassisted	Swale	0.7171
Vertebrate	Footslope	0.7554
Wind/Fire/Ant	Slope	0.8286
Unknown	Swale	1

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NOTE:
This photograph is included on page 163 of the print copy of the thesis held in the University of Adelaide Library.