Limits to revegetation of clay capped landfill sites by Australian native plants

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LIMITS TO REVEGETATION OF CLAY CAPPED LANDFILL SITES BY AUSTRALIAN NATIVE PLANT SPECIES

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Thesis Certification

I, Eleanor J. Hannah, declare that this thesis submitted in fulfilment of the requirements for the award of Master of Environmental Science (Research), in the School of Earth and Environmental Sciences, University of Wollongong, is wholly my own work except where otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Eleanor J. Hannah

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Abstract

The revegetation of closed landfill sites is an important issue due to the large and increasing amount of land involved, and because the demand for that land, and its value, is constantly increasing. If successful revegetation is possible, then these degraded sites provide an excellent opportunity for the establishment of native plant communities in the middle of urban sprawl. Common problems identified with the revegetation of landfill sites have included the use of poor quality soils with low organic matter, low levels of available nutrients, the use of species not suited to the conditions, and landfill gas. The problems with the soils are compounded by compaction, resulting in low permeability and porosity, leading to very low available soil moisture. Little research, however, has been conducted on the revegetation of clay-capped landfill sites in Australia using Australian native plant species. The overall aim of the thesis was to test the survival and growth of indigenous plants at clay capped landfill sites.

I used three landfill sites in western Sydney as case studies. Species that may be suited to the early revegetation of these sites were identified and information available on plant growth of these indigenous was found to be limited. So I initially surveyed the germination potential of a range of the target indigenous species with two pilot studies, one at Site 1 the other at Site 2. At both sites, very low germination rates (0% in 4 species, highest 4.1%) were observed, with the possible contributing factors being low rainfall and subsequent low soil moisture levels and herbivory of seeds and plants.

In order to overcome the fragile germination and early seedling establishment phase, I conducted a planting trial at Sites 1 and 2 using *Acacia linifolia*, *A. ulicifolia*, *Indigofera australis*, *Kennedia rubicunda* and *Lomandra longifolia*. Survival rates from these experiments were also very low, with the main contributing factors inferred to be herbivory, and low soil moisture availability. Importantly, the most successful species in the planting trial was *Lomandra longifolia*, which had zero germination in the seeding trials.

The role of soil moisture in limiting germination or seedling and plant survival was tested in two experiments: a glasshouse germination study; and field study, in which mulching and watering were manipulated. Germination in the glasshouse with daily watering was 10 times higher than that in the field (one-way ANOVA, $F_{x,y} = 243$; P

<0.0001) illustrating that low available soil moisture is a limiting factor in the germination of the tested species. In the field experiment, the addition of the equivalent of 10 mm of rain once a week in the field did not significantly increase germination or seedling survival over 1 year for any of the species tested. A thin layer of straw mulch, however, did result in higher germination and 1 year seedling survival for several species at one of the sites (ANOVA *Hardenbergia violacea* $F_{x,y} = 3.64$; $P = 0.03$ and *Kennedia rubicunda* $F_{x,y} = 22.49$; $P < 0.0001$).

The role of herbivory and seed predation were tested in two other studies. Seed removal in May 1996 was not very high overall at either site, with just over 80% of seed remaining after 1 week. In February 1997, seed removal rates were higher with just 7.1% (Site 2) and 3.3% (Site 3) of seed remaining in the caches after 1 week. The higher seed removal in February was likely to be due to the time of year, with ants being more active in the warmer months. Several problems were encountered with the herbivory study: vandalism, the presence of domestic stock that was not anticipated; and a period of low rainfall. These three factors combined to result in very poor survival rates (11% after 4 months).

I concluded that no one strategy or range of species could be identified for successfully revegetating landfill sites in the short term. However, herbivory, low soil moisture, seed predation, vandalism and ongoing site works, could all limit success in particular circumstances. As a consequence, adaptive management approaches will be needed in developing solutions to particular sites and to ensure new information can be incorporated into ongoing management of a restoration program and the development of a better general understanding about limiting factors.

Chapter 1
Introduction

Landfills are a common means of disposing of waste in most parts of the world. Alternatives to landfills include decreasing the amount of waste, through reducing and recycling, and other disposal methods, such as incineration. In Australia, even with reductions in the waste going to landfill due to recent legislation (e.g., NSW Waste Minimisation and Management Act 1995; and then the Waste Avoidance and Resource Recovery Act 2001), there are still thousands of tonnes of waste requiring disposal every year. If we ceased landfilling today, there are still many thousands of landfills already in existence, which will require restoration and ongoing management.

Landfills are typically located on the fringes of urban areas, far enough away from the population base so impacts from smells and noise are minimal, but, close enough to limit transport costs. As the population grows, the urban areas expand. Land surrounding landfill sites, which was once low in demand and value, becomes in high demand and its value consequently increases. With increasing use of land for population expansion, land available to accommodate conservation of biodiversity decreases. With limits often placed on the future use of landfill sites due to factors such as the production of landfill gas and the uneven settlement of waste, a rehabilitated landfill site has the potential to become an important space for the conservation of native vegetation. This end use can be particularly important in areas where rapid urban expansion has eliminated most areas of native vegetation. Western Sydney is a particularly good example of this (Benson & Howell, 1990b).

There is an increasing trend for landfills, where possible, to be sited in areas of low permeability soils, such as heavy clays, to provide a natural barrier between the waste materials and the surrounding environment. In this situation, the local material is usually used for capping, and where possible, as the overlying soil layer also. There is virtually no research into how endemic plants, especially those that may be adapted to the heavy clay soils that have been used as both capping and soil cover, respond to this environment. There is minimal research into the revegetation of landfills in Australia at all, let alone into the limits to using native species. As there are a substantial number of landfills already in existence, and more

being developed, it is essential, for good site rehabilitation, that we obtain an understanding of how plants might respond in this unusual environment.

The research presented in this thesis was designed to address some of the gaps in knowledge of the potential responses of Australian native plant species by examining the revegetation of landfill sites in the Sydney region with the following characteristics: clay-capped, clayey soil cover, located in an area of naturally occurring heavy clay soils, using Australian native species which naturally grow in the same heavy clay soils. For many Australian plant species, there is little to no information about germination, growth, and root systems. As a result, this research has had to incorporate the collection of basic information about a range of species that could possibly be utilised in revegetation in the study region.

1.1 What are degraded sites?

For the purposes of this research, I define degraded sites as those that have been damaged through human activities. Mining and the disposal of waste are two activities which result in the degradation of land. These activities can leave the land denuded not only of its natural vegetation, but also its original soil.

1.2 Rehabilitation of degraded sites

Active rehabilitation of degraded sites is needed because natural restoration is typically slow (Bradshaw, 1987b), may be inhibited by unfavourable site conditions, and has a high potential for weed invasion. To achieve a successful, fast and cost-effective reclamation, a thorough understanding of the system and the way it operates must be developed (Bradshaw, 1987a). The focus of my research is primarily on revegetation, not on the reclamation of the sites to the vegetation communities that were present before the landfilling activities were commenced, even if the composition of these communities were known in sufficient detail.

Revegetation of degraded sites serves several purposes. Firstly, vegetation, or some other surface cover, provides protection against erosion through reducing the impact of wind and rain. Secondly, vegetation can be used to improve the aesthetics of the site, which may also be a legislative requirement. Thirdly, wildlife habitat can be created with particular animal species facilitated through the type of planting and species used.

Vegetation stabilises soils and protects against erosion in four main ways:

i. Through the interception of raindrops, minimising the direct impact of raindrops on the soil surface;

ii. By increasing the infiltration rate of soils through the presence of organic matter, alive and decaying roots, and the associated biological activity (Styczen & Morgan, 1995). Any increase in infiltration, decreases runoff, as the volume of surface water is reduced;

iii. By forming a physical barrier, slowing the rate of runoff and its potential to move soil particles, and also allowing more time for infiltration to occur. Low-growing vegetation with high surface roughness, such as dense groundcovers, provides the greatest reduction in surface water flow. Dense, low growing, vegetation also has high interception of raindrops, without associated concentration and increased velocities below the plant;

iv. The roots of plants physically bind the soil particles together.

Selecting particular species or types of vegetation can achieve different appearances and effects in revegetation, e.g., grassland for grazing, woodland, plant species known to support particular animals. Native species, which are indigenous to the area, may be desirable as they are already adapted to the local soils, topography and climate. It is also becoming increasingly common for local councils and other consenting bodies, to make the use of native, or indigenous, species part of the conditions of a development approval. When choosing indigenous species, however, the degree to which the original conditions have been changed must be considered. If the original site conditions are substantially altered, such as through the use of different soils, then the potential for using indigenous species may be reduced (see Section 1.5.4).

When undertaking revegetation, it is necessary to consider the conditions present at the site and the desired outcome of the revegetation. In the following section, I describe the general features of landfills as degraded sites and the factors which influence not only their general revegetation, but also their future use.

1.3 Landfills as degraded sites

Landfills sites differ from other degraded sites in five broad features:

i. the production of leachate,

ii. capping,

iii. the production of landfill gas,

iv. uneven settlement of waste, and

v. regulations limiting future land use.

Each of these factors is not, in itself, unique to landfill sites, but the combination is. As all of these factors are found at other degraded sites, research into the revegetation of landfill sites is applicable to other areas, most notably to mine sites and associated stockpiles. Each of the five features, and how they affect revegetation and future land use, is discussed briefly in the following sections.

1.3.1 Landfill leachate

Leachate is the contaminated liquid formed by the breakdown of organic material, and through contact between water and the waste materials as it percolates through the landfill. The type of leachate, and degree of contamination, depend upon: the type of wastes, the age and level of degradation of the wastes, and the length of time the water is in contact with the wastes.

The control of leachate is important because any migration of leachate from the landfill area can lead to the contamination of ground and surface water. Leachate can be controlled

through pumping out and treatment, and/or through lining and capping (see, for example, Lisk, 1991).

1.3.2 Capping

Most modern sanitary landfills are operated using entombment, a process by which the waste materials are separated from the surrounding land and air via various types of synthetic and natural liners and caps (e.g., Lisk, 1991; Caldwell & Reith, 1993). The capping of the waste material has several aims:

i. To prevent the spread of wastes from the landfilled area into the surrounding environment;

ii. To prevent contact between people, animals, and the wastes;

iii. To prevent water from percolating from the surface, into the waste, where it will form leachate;

iv. To slow the movement of any leachate which may have formed, out of the landfilled area. This function is mostly served by the lining of the landfill, but, leachate may well up and pool in the upper levels of the landfill;

v. To restrict the movement of landfill gas into the cover soil and atmosphere.

Capping is also used at mine sites for stockpiles of contaminated material (e.g., Williams, 1995; Menzies & Mulligan, 2000).

1.3.3 Landfill gas

Landfill gas can be odorous, explosive and limiting to vegetation growth. It is composed primarily of methane and carbon dioxide, formed during the breakdown of organic (putrescible) material (Barry, 1987). Depending on the composition of the waste, its age, and its moisture content, landfill gas can be produced for several decades (Lisk, 1991).

The odour of landfill gas is not due to the methane (which is odourless), rather, to the presence of nitrogen and/or sulfur containing organics and/or hydrogen sulfide. Hydrogen

sulfide is not present at all landfill sites. Where it occurs, it is a problem due to its odour and its toxicity to plants (Crawford, 1976) and animals.

The greatest hazard with landfill gas is from methane, which is combustible in air (concentrations of 5-15%). Methane is also a problem because it is a greenhouse gas. In the soil, it is generally considered to be harmful to plants (Section 1.5.6.1). The risks associated with this gas, lead to many controls being placed on the future use of landfill sites (Section 1.3.5). In many modern landfill sites, landfill gas is collected and used as a fuel. In this way, the gas goes from being a harmful and problematic waste product, to one which is utilised.

1.3.4 Uneven settlement of the waste

The surface of landfills settles or recedes as the deposited wastes break down, and are compressed by the layers of waste and capping above. The degree of subsidence varies depending upon the types of waste deposited, the extent to which the wastes were compacted when deposited, the size of the landfill (particularly the depth of the waste), the time period over which the wastes were deposited, the level of moisture in the waste and the temperature. The settling of the waste is uneven as the types of wastes throughout the site, and their method of placement, is variable (e.g., Aplet & Conn, 1977).

1.3.5 Limitations on future land use

Due to the four factors already described (production of leachate, the importance of the capping, landfill gas and the uneven settlement of waste) future land uses of landfill sites are generally very restricted (Aplet & Conn, 1977). All of these factors can be overcome and there are success stories of landfills that have been used for parks, entertainment areas and other buildings (Bradshaw & Chadwick, 1980; Corkery & Corkery, 1985). Developments such as these are very expensive, so completed landfill sites have often been abandoned (e.g., Flower *et al*., 1978; Wong, 1988; Rawlinson *et al*., 2004).

Another consideration in the future use of a landfill site is the challenge of maintenance. For new landfills there are increasing legal requirements for maintenance such as leachate and

landfill gas monitoring, checking the capping and the revegetation (e.g., Rawlinson *et al*., 2004). For older sites, however, there were no such requirements, so maintenance of the site is dependent on the landuse of the site being considered worthwhile and the area being utilised.

1.4 Challenges to rehabilitation

I have divided challenges to degraded land rehabilitation into two broad areas: those common to degraded sites generally and relevant to landfill sites; and those that are more specific to landfill sites. General factors relating to the rehabilitation of degraded sites are provided in Sections 1.4.1. Following this, in Section 1.4.2, I review research into challenges of landfill rehabilitation.

1.4.1 General challenges to the rehabilitation of degraded sites

There are many factors which need to be addressed in regards to the rehabilitation of degraded sites. Firstly, where the land has been stripped bare, there is no protection from sun and wind (Black & Trudinger, 1976). There may be long distances to the nearest native vegetation and therefore to seed banks. If seed is able to get to the area and grow, it is commonly seed from weeds which, if they establish, will compete with future vegetation (see Section 1.5.3). Lack of availability of seeds and seed dispersers is even more prevalent in areas where vegetation is patchy with few links, as is often the case in urban areas (e.g., Robinson & Handel, 2000).

The soils at degraded sites, if they are present at all, are often compacted and low in nutrients and organic matter (see Section 1.5.5). Under these conditions, decisions need to be made whether the "soil" material will be used as it is, whether changes will be made to the soils that are present, or if new soil material will be brought onto the site.

The presence of poor quality soils and weeds mean that even if seed from desirable species is making it to the site, there is no assurance that germination and/or seedling survival will occur.

Robinson and Handel (2000) found there was a weak correlation between the numbers of seed arriving at patches on an old landfill site and the number of new seedlings.

Another common problem in the rehabilitation of degraded sites is the use of species not suited to the site conditions (e.g., Gilman *et al*., 1982; Hannah, 1997). This can come about in three ways:

i. Lack of understanding of the site conditions, especially in relation to changes to the original site conditions;

ii. Lack of knowledge of the plant species and how they grow in different environments;

iii. Personnel with responsibility for management and rehabilitation of degraded sites having too little knowledge of revegetation, but, being required to make choices relating to species and planting. With increasing legislative requirements that reports and detailed closure plans be prepared, these problems are generally decreasing. They do, however, still occur (Hannah, 1997) and are an ongoing problem at old landfill sites where the legacy of poor planning continues.

1.4.2 Challenges to rehabilitating landfill sites

After capping, a soil layer is deposited, to provide a protective barrier for the cap and a zone for vegetation growth. Topsoil is present at landfill sites where landfilling is progressive and soil from new areas is placed on recently filled areas, or where soil has been stockpiled. For other landfill sites there may be no topsoil available. More information on the soil layer is presented in Section 1.5.5.

The production of leachate, landfill gas, and the uneven settlement of waste (see Section 1.3) are also important factors in the rehabilitation of landfill sites. In order to assess some of the issues found at different types of landfill site, an overview of research into the limitations to landfill rehabilitation is provided in Section 1.4.2.1. Following this I provide an overview of plant excavation studies at landfill sites (Section 1.4.2.2) and limitations that have been placed on the types of vegetation which can be grown on landfill sites.

1.4.2.1 Limitations to the revegetation of landfill sites

Early research into the revegetation of uncapped landfills in the USA found that landfill gas, with associated elevated methane and carbon dioxide, and low soil oxygen, were limiting to vegetative growth on and around landfill sites (see, for example, Gilman *et al.*, 1979; Gilman *et al*., 1981b). Other factors found to be limiting to growth and survival were thin soil cover, low soil moisture content, low water holding capacity, compaction, high bulk density, high soil temperature, and the use of sensitive or inappropriate species (Gilman *et al*., 1981a; Gilman *et al*., 1981b). These studies highlighted the importance of the soil in the successful revegetation of landfill sites, and that poor soil material is typically used in the cover of landfill sites.

Insley and Carnell (1982) in work on uncapped landfills near Essex, England, described the main limiting factors to revegetation as reduced oxygen levels restricting root growth thereby leading to instability of the plant and water stress. These factors were compounded by shallow soils, compaction and soils with low water holding capacity.

In a study of the vegetation at 40 closed landfill sites in Finland, the main limiting factors to natural revegetation were: thin, poor quality soils and the young age of the refuse (Ettala *et al*., 1988). Ongoing site disturbance from vehicles and continued alteration of the surface were also found to be important factors (Ettala *et al*., 1988). Ettala (1988) also found landfill gas to be a localised problem only. Where soil cover was sufficiently deep, where nutrients and water holding capacity of the soil were at reasonable levels, and where ongoing disturbance was minimised, the revegetation at closed landfills could be very successful (Ettala, 1988; Ettala *et al*., 1988; Ettala, 1991).

Several groups of researchers have studied old style landfills (not having geotextile liners or any of the other more recent developments) in the Mersey Forest and Red Rose Forest regions in the UK. Wong (1988) found that well vegetated areas at two of the landfills had lower levels of methane, and that there were significant high correlations between soil nitrogen levels and dry weights of vegetation. Dickinson (2000) found that limitations to revegetation at some of these landfill sites included the presence of high levels of copper, zinc, nickel and arsenic; soil compaction; water logging; the presence of surface leachate; and in places the

presence of methane and carbon dioxide with low levels of oxygen. Rawlinson *et al*. (2004) planted 39 plots across 11 of the sites with 21 different woody species. Weed competition was found to be the greatest inhibitor to plant establishment in the first year. Overall, the researchers found a high degree of variability both within site and within plots. They argued that this variability, along with the differences between landfill sites, makes it difficult to make general recommendations on the use of particular species for revegetation at other landfill sites. This research in NW England is ongoing and future observations will be very interesting as a comparison with results of the research presented in this thesis.

1.4.2.2 Plant excavation studies at landfill sites

Perhaps the first formal excavation study involving vegetation growing on a landfill was by Gilman *et al*. (1981b). Seven-year-old *Tilea americana* trees were excavated from a soil cover on top of, and adjacent to a sanitary landfill in New Jersey, USA. The plants excavated were grown in trenches with different landfill gas barrier treatments, or controls with no treatment. Eight plants were excavated from trenches on the landfill with three different treatments and a control with no treatment, while four were grown in control plots off the landfill with no treatment. The three treatments on the landfill were: 30 cm clay lining, 30 cm clay lining plus vertical gas vent pipes, and 4 mm plastic sheet over 30 cm road gravel plus vertical gas vent pipes (Gilman *et al*., 1981b). The depth and pattern of the roots was recorded. Plants grown on the landfill in the non-trench area had significantly shallower roots than all other treatments. There was a negative correlation between total root length and the percent of methane and carbon dioxide; and a positive correlation with the percent of oxygen in the soil (Gilman *et al*, 1981b).

Robinson and Handel (1995) excavated 30 plants from 12 species on a 7-year-old landfill site in New York. This site had a 45 cm compacted clay cap overlain by 10-30 cm of soil. The majority of the roots were growing above the clay cap, with only stubby feeder roots penetrating into the capping, but only 1 cm deep, up to 6 cm in cracks. They concluded that the impediment to root penetration was both physical (due to the high bulk density), and chemical (due to the low pH resulting from pyritic material present in the clay cap). This study was followed by more extensive experiments with similar results (Handel *et al*., 1997;

Parsons *et al*., 1998). These findings are not surprising, given the large difference between the cover soil and the capping material, as well as the capping material having both physical and chemical restrictions to root penetration. Further work is required, however, for sites where there are fewer controls, fewer toxic materials present in the capping and less differences between the capping and the cover soil.

1.4.2.3 Restrictions on the types of plants permitted on landfills

Due to the generally thin nature of the soil layer at completed landfills, and the need to protect the cap, restrictions may be placed upon the planting of trees, or any type of woody plant, on top of landfill sites (Dobson & Moffat, 1993). Dobson and Moffat (1993, 1995) undertook a review of the literature relating to root growth and the conditions at landfill sites. They concluded that at modern engineered landfill sites, the HDPE (high desnity polyethylene) and natural clay capping, sufficiently restricted the growth of plant roots such that restrictions on the types of plants grown were not necessary. In these reviews, Dobson and Moffat also noted that landfills are frequently covered with compacted, infertile soils typically low in organic matter and microflora. These factors will all restrict root growth, making it even less likely that the plant roots will grow down to the cap, let along through it. Research by other authors has supported these reviews in finding that careful layering of restrictive material can prevent the roots of even large species from penetrating a cap (e.g., Robinson & Handel, 1995; Handel *et al*, 1997). As such detailed designs are very expensive, consideration needs to be given to alternatives.

Many landfills are located in areas of heavy, impermeable clay, precisely because the environment provides a natural barrier and liner. A natural clay layer as a liner is usually much thicker that an imported liner, but, it is less controlled. When landfills are located within an area of heavy clay, the site material is also usually used for capping. It is important to know how species respond at these older style landfill sites, which did not have carefully engineered caps, especially if the species used are adapted to growing in low nutrient, low permeability soils and are drought adapted.

If roots grow into, and then through, the cap, this may allow water infiltration into the wastes. There would seem little doubt that a perfectly engineered and installed cap would, at least in the short term, be impenetrable to roots. Any cracks formed from subsequent movements or drying may, however, be accessible to the plant roots. Once the root is in the crack, the turgid pressure may be sufficient to widen the crack. If plant roots grow through the top layers of the cap, further growth is likely to be restricted by lower oxygen levels and increased levels of landfill gas in the lower layers of the cap.

For larger/taller vegetation, another consideration is the potential for plants being toppled by windthrow. On a well vegetated site, it has been argued that windthrow will not occur and will not be a problem (Robinson & Handel, 1995; Dobson & Moffat, 1993, 1995). Where soils are poor and rainfall sporadic, such as in the Western Sydney area, the vegetation is often open with large shrubby and grassy areas between the trees. On a landfill which had been grassed or vegetated with a low shrubby layer, a tree would have little or no support from surrounding neighbours. The arguments against windthrow would not appear to work in this situation. More research into different species growing in a wide variety of conditions, including observation of their root systems, is required.

Water that filters into the soil is drawn up by the plant roots, through the upper parts of the plant, then out through the leaves as transpiration. Thus, plants both increase infiltration of water into the soil, allowing the plant to survive and grow, and remove water through transpiration. The removal of water in this way is beneficial on landfill sites as it can prevent the water settling on the cap, possibly leading to infiltration into the waste and subsequent formation of leachate.

Plant roots change the soil structure by forming small channels in the soil (Mitchell, *et al.*, 1995) and adding organic matter (Murphy, 1991). In poorly drained soils, air can enter along the roots (Murphy, 1991; Wild, 1993). If oxygen in air can move along the root line through changes to the soil structure, it would be reasonable to argue that, if the roots were to penetrate the cap, then the landfill gas could move along the root line further reducing the amount of oxygen in the soil available to the plant. The size of the roots also has a major role to play. A root channel 50 mm wide has the potential to transmit a lot more air, gas and water, than one 5 mm wide.

This section illustrates some of the conflicts in landfill research and management as vegetation can be shown to have both a positive and a negative impact upon the soil layer of the landfill and, potentially, the cap as well. Careful consideration needs to be given to the characteristics of the landfill site (including the types of wastes, the method of capping, the climate and the soils), the future uses of the site and the characteristics of the plants to be grown (if known). It is important to keep these variations in mind, as this helps to explain why both the research and its conclusions are quite varied. By considering these differences, and examining the research undertaken in other countries, the research questions tackled in this thesis were formulated.

1.5 Individual factors affecting rehabilitation

In the following sections I discuss individual factors that can affect revegetation of landfill sites. Many of these factors are interrelated, such that some of the effects are compounded. Whilst there are many other factors which may be present at any given site, the factors discussed in the sections below are widely found at many degraded sites, and are relevant to the revegetation of landfill sites.

1.5.1 Climate

Climate can affect the revegetation in numerous ways; indeed, in arid and semi-arid areas, climate may be the limiting factor (e.g., Grantz *et al*., 1998). Bradshaw and Chadwick (1980) described how land with no vegetation cover is hotter for three reasons: (i) the soil is often dark leading to greater solar energy absorption; (ii) limited convection; and (iii) limited or no evaporative cooling.

The amount, frequency and intensity of rainfall can all significantly affect the revegetation of a degraded site. Heavy rainfall can wash away unprotected soil and lack of rain is exacerbated by higher transpiration from wind exposure and soils with poor water holding capacity (Section 1.5.5.6). Low rainfall, or periods of low rainfall, can restrict soil moisture and plant survival (Section 1.5.5.6).

The climate of an area can affect the timing of revegetation works and the maintenance and management required.

1.5.2 Herbivores

Herbivores have been found to be a limiting factor in the revegetation of many sites (e.g., Ashby, 1997, Grantz *et al*., 1998; Ruhren & Handel, 2003; Koch *et al*., 2004). It is thought that the higher rate of herbivory is due to: the small size of the plants; the age of the plants (young); and their exposure, affording them less visual and olfactory protection. While many studies have found mammalian herbivores to be limiting to revegetation, Meiners *et al*. (2000) found that insect herbivory can also result in increased mortality of seedlings. Seed removal, with or without consumption, has also been found to be an important factor in the revegetation of many sites (Campbell, 1982; Abbott & Van Heurck, 1985; Andersen & Ashton, 1985; Handel & Beattie, 1990).

1.5.3 Weeds

Where soils are of reasonable quality and the climate is favourable, then weeds can quickly colonise the surface. As mentioned above, Rawlinson *et al*. (2004) found that weeds were a limiting factor to plant establishment at closed landfill sites in England. With the rehabilitation of landfill sites, one of the factors to consider is when conditions and the soils are selected to make them more suited to plant growth, the likelihood and severity of weed growth and competition is increased (Roberts & Roberts, 1986). Weed competition leads to slower rehabilitation of desired species, with more maintenance and subsequent higher costs.

At degraded sites, such as landfills, where topsoil is absent, the cover material used can affect the amount and type of weed seed present (see Section 1.5.5).

1.5.4 Species selection

The selection of species that are suitable for growing in the prevailing conditions is also essential for successful plant rehabilitation (Bradshaw, 1983; Simons, 1976; Handel *et al*.,

1994; Hannah, 1997; Robinson *et al*., 1992). Identifying suitable species is not a simple process. One of the features of degraded sites is that the original conditions have been changed, so species that were originally growing on the site may no longer be suitable (Black & Trudinger, 1976; Simons, 1976; Bradshaw, 1983). Before suitable species can be selected, site conditions need to be identified: how much rainfall and when, topography, soil characteristics, and the presence of herbivores and potential pollinators (Handel *et al*., 1994). This process is complicated on degraded sites where problematic conditions may be present, e.g., landfill gas or heavy compaction, where literature on how specific plant species grow in these conditions is not available.

1.5.5 The soil layer

The soil layer, its thickness, composition, physical and chemical characteristics are all important factors in the revegetation of a degraded site. The factors which are most relevant and important in the revegetation of landfill sites are discussed below.

1.5.5.1 Availability of topsoil

The main problem with using topsoil, is that it is a very limited commodity, especially in countries such as Australia where many areas are covered with poorly developed soils (CSIRO, 1983). Unless topsoil had been stockpiled prior to the initial activities, it would have to be taken from another area. On sites that were mined prior to landfilling, there may be a lag time of 20 years or more between the first stripping of the land and the completion of landfilling activities. If works are carried out progressively, topsoil from a new area can be used to cover the previous area. This is, however, only feasible on large sites and does not overcome the problem for most existing sites. On sites where there has been previous activity, topsoil may have already been removed for use elsewhere, or otherwise affected, such as, through farming or vegetation removal and erosion.

An alternative to topsoil is the use of soil mixes containing waste materials, such as, sewage sludge (e.g., Bradshaw & Chadwick, 1980; Ettala, 1991; Cox & Whelan, 2000; Sellers *et al*., 2001; Gregory & Vickers, 2003). Many of these are, however, still in the experimental

stage and approval to use them in urban areas may not be granted except under very controlled conditions. The third option is to use subsoils and other low quality soils. This is the most likely option at many landfill sites because it allows the use of whatever materials are available, which is cheaper, and may therefore allow for a thicker cover to be installed.

A lack of topsoil also means no local seed bank is available. If subsoils are used, then the presence of a soil seed bank is seriously limited (e.g., Panetta & Groves, 1990). On the other hand, if soils are brought in from elsewhere, they may contain weed seeds that can then inhibit the growth and establishment of desired species (see Section 1.5.3).

1.5.5.2 Soil compaction

Soil compaction can have serious impacts on the rehabilitation of degraded sites through a reduction of both permeability and pore spaces, leading to low levels of soil moisture and oxygen, and mechanical restriction to root growth (e.g., Wild, 1993; Robinson & Handel, 1995).

On top of the compacted clay cap is the soil layer, which should not be compacted. As the soil is usually installed by heavy machinery, some compaction is inevitable. Where the soil material has been compacted, the surface needs to be scarified, or otherwise worked to try and minimise the effects (e.g., Black & Trudinger, 1976; Ashby, 1997). Some researchers have studied sites where the cover material was loose tipped, resulting in lower compaction and in some cases, reasonable revegetation (Moffat & Bending, 2000; Sellers *et al.*, 2001).

1.5.5.3 Salinity

High levels of soil salinity are common in subsoils (especially in Australia) where the salts are leached from the upper soil layers under the influence of rainfall, and can be deposited with the movement of groundwater. If the soil layer at a landfill site is composed of subsoil, then it is reasonable to assume that the soils may be saline. This can cause problems in the revegetation of the site as concentrations of salts in the soil can influence both germination and plant growth.

Ayers and Hayward (1948) showed that there were two processes by which soil salinity affected germination. Firstly, there is a decrease in water uptake, and secondly, there can be an uptake of ions to toxic concentrations. Increased salinity results in a reduction in both germination vigour and percentage (Bernstein & Hayward, 1958). Barrett and Jennings (1994) found that germination was inhibited in saline conditions for many Atriplex species, and that the seed remained dormant until the salinity reduced. Ayers (1952) suggested that the germination is likely to be delayed due to the reduction in water uptake, while the reduction in percentage may be due to the ion toxicity.

1.5.5.4 Soil pH

High or low pH can result in a restriction to nutrient availability and uptake (Gemmell, 1977). Soils with pH less than 4 are generally toxic to plants (Gemmell, 1977). Carbon dioxide, from landfill gas, in the soil can result in a decrease in soil pH (e.g. Robinson, 1989), as well as influencing oxygen concentration and root respiration.

1.5.5.5 Soil nutrients

Disturbed soils often have low nutrient concentrations (e.g., Black & Trudinger, 1976; Bradshaw & Chadwick, 1980). If root development is restricted due to a lack of nutrients then the addition of fertiliser may prevent deaths from dehydration (Bradshaw, 1983). Bradshaw (1983) also argued that all plant growth requires an adequate supply of nutrients, therefore, using species tolerant to low levels of nutrients will not remove the concern over a lack of availability.

1.5.5.6 Soil moisture

There are many factors which can affect both total and available levels of soil moisture. Total soil moisture is a product of added water, porosity, pore size, grain size and organic matter content. Compaction decreases the moisture content of soil through a reduction in both pore space and permeability. Low soil moisture can also lead to mechanical restriction to root

growth (Wild, 1993). Each of these factors is relevant for landfill sites, so it is expected that low soil moisture would be limiting to vegetation establishment at many landfill sites.

Where the ground is not completely moist at the time of planting, the addition of water is beneficial (Venning, 1988). After this, consideration can be given to the use of artificial watering and/or the use of mulches or other aids to improve soil moisture availability. It is not necessarily a simple matter to provide artificial watering. Water may not be readily available. Even if it is, application may be difficult as landfill sites are often domed and their proximity to urban areas can make them a ready target to theft or vandalism, causing loss of or damage to watering systems. A revegetation program that is designed to depend on a watering system may be fragile. It could be argued, therefore, that the cost, maintenance requirements and risks involved with artificial watering can outweigh any potential benefits.

1.5.5.7 Soil oxygen

Low levels of soil oxygen may develop on capped landfills through a number of processes. Firstly, through the migration of landfill gas from the waste material, through the cap and up to the "soil" layer. As the gas migrates through the soil, levels of soil oxygen can be reduced through displacement, or are used in the conversion of methane in air, by methanogenic bacteria, to water and carbon dioxide. The degree to which this occurs will depend upon the capping, the types of wastes, and the age of the landfill. Soil compaction also contributes to low soil oxygen through a decrease in permeability and pore spaces (see Section 1.5.5.2).

Low soil oxygen levels can restrict plant growth at all stages, from germination to later root growth (e.g., Cannon, 1925; Ashby, 1961; Crawford, 1976). The sensitivity of a plant to low soil oxygen levels varies both between species (Cannon, 1925; Crawford, 1976) and between populations of the one species. Some species are also known to increase levels of soil oxygen by pumping oxygen into the soil through the roots (Hook *et al*., 1972; Crawford, 1976; Wild, 1993). These species may be more resistant to the effects of landfill gas as they put oxygen back into the soil. Arthur *et al*. (1981), found that red maple, a flood tolerant species, was more tolerant of landfill gas in the soil than was sugar maple, not a flood tolerant species.

1.5.5.8 Soil temperature

Elevated soil temperatures have been found at closed landfill sites (Flower *et al*., 1981). The breakdown of organic matter in the landfill results in the generation of heat. This may reduce the uptake of nutrients as well as the germination potential of many species. The heat can also result in the upward movement of landfill gas, including carbon dioxide and methane, which are both denser than air. Therefore, increases in soil temperature may result in an increase in levels of methane and carbon dioxide in the upper levels of the soil. In low soil oxygen conditions, root growth has been found to be faster at lower temperatures (Cannon, 1925), and it can be expected that if both low soil oxygen levels and elevated temperatures are present in the soil cover then root growth would be restricted.

1.5.6 Landfill gas and its components

As mentioned in Sections 1.3 and 1.4, landfill gas can be a limiting factor in the successful revegetation of landfill sites where gas is present in the soil. Of the many components of landfill gas, the literature suggests that ethylene (e.g., Smith & Restall, 1971; Tosh *et al*., 1993), hydrogen sulphide (Crawford, 1976), carbon dioxide and methane can negatively impact either the roots or above-ground material (e.g., Crawford, 1976; Gilman *et al*., 1981b; Gilman *et al*., 1982). Other research (e.g., Arthur *et al*., 1981), has found that some species more tolerant of flooded conditions, with low soil oxygen, were also more tolerant of landfill gas in the soil.

At capped landfill sites, there is usually little opportunity for landfill gases to come into contact with the aerial parts of plants. In the soil, however, landfill gases cause several problems.

In the following two sections, I discuss the two main components of landfill gas, methane and carbon dioxide, associated with restricted plant growth and survival (e.g., Gilman *et al*., 1979).

1.5.6.1 Methane (CH_4)

Methane is a colourless and odourless gas produced in landfills by the biomethanogenesis of organic matter in anaerobic conditions. This process also produces carbon dioxide and there are several bacteria involved, for an overview of the processes see Chynoweth, 1996. The presence of methane in the soil is not considered to be directly toxic to plants, rather it is the aerobic decomposition of methane by bacteria with the resulting formation of carbon dioxide which can affect plant growth (Hoeks, 1972; Barry, 1987). This process has several affects which may be detrimental to plant growth and survival: decrease in soil oxygen; increase in carbon dioxide (Barry, 1987); where the decomposition is incomplete other products such as methanol, formaldehyde and formic acid are produced; and the reaction is exothermic, resulting in an increase in soil temperatures (Barry, 1987), which may allow more carbon dioxide and methane to rise up through the covering material (see Section 1.5.5.8).

1.5.6.2 Carbon dioxide (CO_2)

Carbon dioxide is an odourless gas produced on landfill sites though the aerobic and anaerobic decomposition of organic matter. Carbon dioxide is also produced in the aerobic decomposition of methane. If carbon dioxide from the landfill migrates through the soil layer, soil oxygen may be reduced through displacement.

The presence of excess carbon dioxide in the soil inhibits plant growth by restricting absorption of water and nutrients by the roots (Chang & Loomis, 1945). The response of plants to carbon dioxide in the soil varies between species (e.g., Cannon, 1925; Arthur *et al*., 1981).

1.6 Western Sydney as a suitable study location

The focus of this research is on landfills which were located in areas with natural heavy clay as the liner and where the local clay material was used for capping. Another feature of these sites is that the soil cover layer is generally sourced locally, and, the indigenous vegetation

would naturally grow in that material. The other important characteristic was that several sites were available, either within, or on the fringe of, an urban area, where demand for land is high. Western Sydney meets all of these criteria, and was therefore selected as a study location.

Western Sydney has an increasing population with urban sprawl putting greater demand on land that was once open space, quarries and farms. The large population of Sydney (4.2 million in 2002, Australian Bureau of Statistics) has resulted in the construction of a large number of landfills. Clays derived from the Wianamatta Shales are the main soil type in the Western Sydney area (Bannerman & Hazelton, 1989) (see Section 2.1.2).

Under relevant legislation, these landfills could not legally permit food wastes, but, could accept paper, cardboard, and plant material including grass clipping, branches and logs, all of which will putresce over time to produce landfill gas (see Section 1.3.3).

In a system where "soil" on top of the cap was made from the same subsoil material as the cap itself, restriction to root growth from the soil layer into the capping would be purely due to the increased compaction with resulting decrease in permeability, etc. (see Section 1.5.5.2).

1.7 Specific aims of this study

There were six main issues I aimed to address in this research:

i. To provide an overview of research into the revegetation of landfill sites and limiting factors which have been identified;

ii. To use the information found, plus local information, to identify potentially limiting factors to vegetation growth on clay capped landfills in Western Sydney;

iii. To develop a list of species from the literature, and similar environments, which may be suitable for revegetating these landfill sites. Further I aimed to conduct a series of trials using these species to identify the limiting factors on the Western Sydney landfill sites and assess the success of the method of choosing species;

iv. To use the trials to identify the most appropriate method of establishing native plants on these landfill sites, e.g., direct seeding or planting;

v. To examine the root systems of plants established on the landfills to determine the shape and extent of the root system and the degree to which roots penetrated the cap;

vi. Finally, to use all the results to discuss the potential of these sites, and clay capped landfills in general, for establishment with native vegetation.

The outline of the thesis structure and the various studies I undertook to achieve the aims is provided in Figure 1.1.

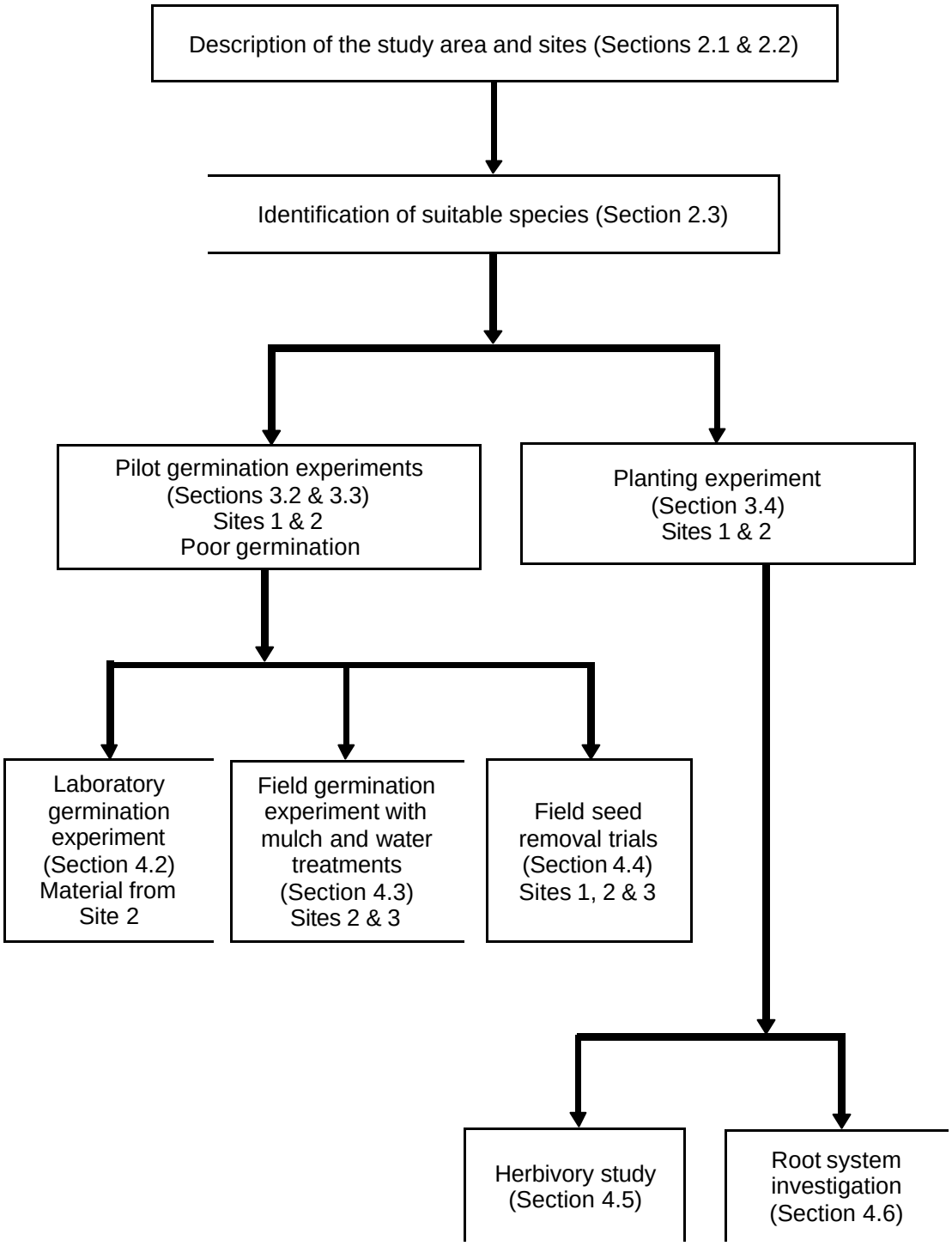


Figure 1.1 Flow chart of thesis structure

Chapter 2
Characteristics of the study area, the experimental sites and species selection

This research into the revegetation of clay capped landfills was conducted on three landfill sites in the Western Sydney region. These sites are located on the Cumberland Plain, in areas characterised by clay soils and a rapidly expanding urban population into what was previously largely grazing land. Before settlement, this region supported eucalyptus woodland and open forest.

In this chapter, I describe the environment of the area (Section 2.1), the three study sites (Section 2.2), and the process for selection of suitable species for use in experiments at these sites (Section 2.3). For each of the suitable species identified, I describe the seed, investigation of the treatments needed to stimulate germination, the source of seeds and the germination treatments (Section 2.3.3). Additional information on methods specific to individual experiments is provided in later chapters.

2.1 Environment of the Cumberland Plain

The general environment of the Cumberland Plain, where the three study sites were located, is described in terms of climate (Section 2.1.1), topography and soils (Section 2.1.2) and general flora and fauna (Section 2.1.3).

2.1.1 Climate

The general climate of the Cumberland Plain is classified as warm temperate (Elliot & Jones, 1989) with warm to hot summers and cool to cold winters. Seasonal variations are high across the whole area with greater variation on moving west across the Cumberland Plain. On the eastern edge, mean daily minimum and maximum temperatures in winter are 6.9°C and 18.0°C and in summer 17.0°C and 27.8°C (Station 066124, Parramatta North, Bureau of Meteorology, 2005; Figure 2.1). On the more variable western side, daily minimum and maximum temperatures in winter are 4.1°C

and 17.9°C and in summer 16.3°C and 29.1°C (Station 067021, Richmond – UWS Hawkesbury, Bureau of Meteorology, 2005).

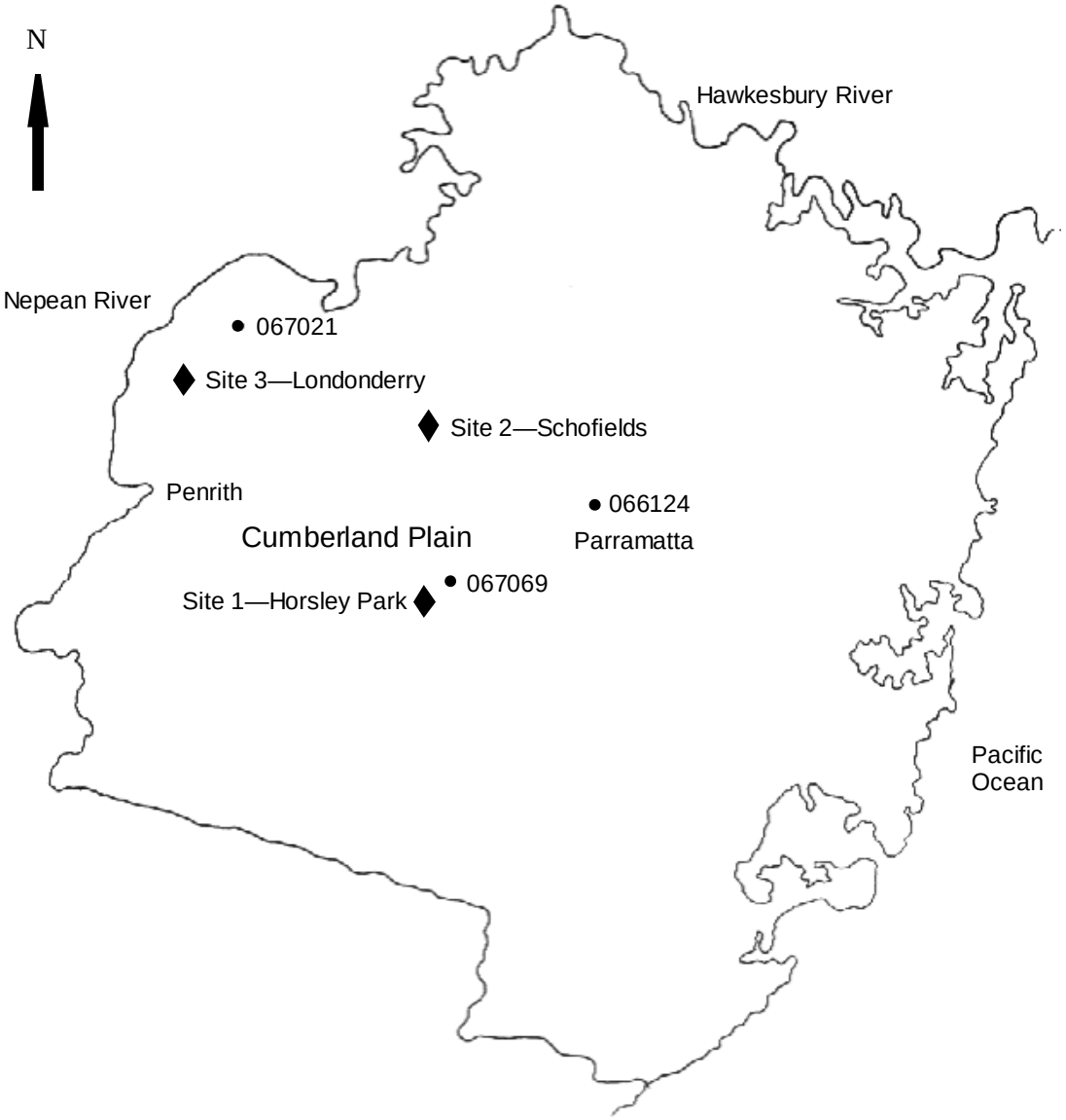


Figure 2.1 Location map of the three study sites within the Sydney region and the Bureau of Meteorology stations (●)

The variability around these averages is quite high with the lowest and highest temperatures recorded being –7.2°C (Richmond – UWS Hawkesbury) and 44.5°C (Parramatta North) respectively (Bureau of Meteorology 2005). Diurnal variations are also high, with day-night temperature differences commonly more than 10°C (Bureau of Meteorology, 2005).

Frosts are variable across the area with more frosts occurring in the west. On the eastern edge of the Cumberland Plain, there are, on average, only 2-3 days below 2°C per annum, on the western edge there are 40 (Bureau of Meteorology, 2005).

Average annual rainfall for the Cumberland Plain is low, under 1000 mm per annum, with much of the Plain receiving less than 900 mm per annum. As with temperature, rainfall on the Cumberland Plain is also very variable, both across seasons and between years. Rainfall is higher in summer and autumn and lower in winter and spring, largely due to the influence of moist easterly airstreams in summer and dry westerlies in winter. Variations in annual rainfall are readily illustrated using the figures recorded at two of the local stations: Prospect Dam (Station 067069) mean annual rainfall 871.3 mm, 10^{th} and 90^{th} percentiles 548.1 and 1225.2 mm, and the highest rainfall recorded on a single day 321.0 mm; Richmond – UWS Hawkesbury (Station 067021) mean annual rainfall 801.3 mm, 10^{th} and 90^{th} percentiles 527.6 and 1074.7, and the highest rainfall recorded on a single day 309.4 mm (Bureau of Meteorology, 2005).

2.1.2 Topography and soils

The landscape of the Cumberland Plain generally consists of gently undulating hills less than 100m above sea level (Forster *et al*., 1977). Most of the area is formed from the Wianamatta Shales resulting in deep, clay rich soils. The main drainage system is the Hawkesbury-Nepean River. Areas adjoining the river system contain lenses of alluvial material (Benson, 1992), which are generally higher in sand and silt.

At my study sites, the topsoils had been largely removed during the clay mining activities. The subsoils observed during the research were formed from the Wianamatta Group shales and are characterised as deep heavy, highly plastic clays of low permeability (Old, 1942), low pH, low in nutrients, e.g., phosphorus, calcium, and nitrogen (Bannerman & Hazelton, 1989; Benson, 1992), low available water capacity

(Bannerman & Hazelton, 1989), high salinity (Old, 1942; Bannerman & Hazelton, 1989), low organic matter content, and high aluminium toxicity (Bannerman & Hazelton, 1989). Disturbed soils are readily eroded under concentrated flow and, due to the low permeability, are readily waterlogged.

2.1.3 General flora and fauna

The vegetation of the Cumberland Plain is largely open woodland dominated by *Eucalyptus moluccana* and *E. tereticornis,* with the understorey generally being low and open (Benson & Howell, 1990a). Much of the Cumberland Plain vegetation has been removed or highly disturbed and is now listed as an endangered ecological community under the NSW Threatened Species Conservation Act (1995). The other vegetation type of relevance to this study is the Castlereagh Woodlands (also listed as an endangered ecological community), which occurs in areas of heavy clay interspersed with lenses of alluvium, with the resulting vegetation having characteristics of both heavy clay and sand communities.

Plant growth on the Cumberland Plain is limited by low temperatures during winter, and commonly low available soil moisture, low levels of nutrients, especially phosphorus, and relatively high levels of salinity (Old, 1942). As a result of these limitations, plants growing in the area are generally adapted to drought, heavy clay soils, and in many cases, low nutrients and high salinity.

There are many herbivores present on the Cumberland Plain. Most are introduced species, including cattle, horses, goats, hares and rabbits. Eastern grey kangaroos (*Macropus giganteus*) are also present in some areas, where more of the original vegetation remains. When undertaking a revegetation program, information on the presence of herbivores is essential for designing appropriate site-management methods. The occurrence of herbivores and the type of fencing present were recorded, for each of my study sites.

2.2 Characteristics of the experimental sites

The three sites used for field experimentation were at Horsley Park (Site 1), Schofields (Site 2) and Londonderry (Site 3) (see Figure 2.1). Each of these sites was previously mined for brick and pipe-making clay. The mining operations resulted in one or more pits, and stockpiles of uneconomical, clayey soil material. Services required for the mining operations, such as access roads, drainage structures, and electricity, were present at each of these sites.

All of the landfills used in the study were classed under the NSW Waste Minimisation and Management Act (1995) as being non-putrescible (see Section 1.6). The main wastes accepted at each site were builders refuse (rubble and timber) and low-level contaminated soils. Each layer of waste was covered with a layer of clayey soil, usually derived from the stockpiles on the respective site. The filling continued above ground to form a mound or dome.

Once the final domed landform was reached, the entire landfilled area was capped with a minimum of 600 mm of low-permeability clay soil sourced from the site and/or from surrounding areas on the Cumberland Plain. There was no separation of soil horizons at the time of stockpiling and, thus, the capping and cover material had no typical soil horizons at the time of placement.

Landfills settle over time, from decomposition of the waste material and compaction from overlying layers, resulting in a decline in the grade of the slopes. It is expected that this would be much less than that experienced at municipal (council) landfills due to the much lower putrescible content of waste materials accepted at the study sites.

At each of the sites, groundwater and leachate monitoring wells were installed and tested for a range of water quality characteristics. During the study period, the leachate remained within the landfill area and there was no reported evidence of contamination of the ground or surface water. On several occasions after capping, the surface of the landfills was monitored for the presence of methane, carbon monoxide and oxygen. No methane or carbon monoxide was detected (lower detection levels for both were 0.1% in air) and levels of oxygen remained within normal atmospheric levels (20%).

Much of the original vegetation around the experimental sites had been removed or disturbed, with only small patches remaining, mainly around dams and property margins. Due to the highly disturbed nature of the sites, and the movement of soil within and between sites over a period of 5 to 20 years, it cannot be assumed that this flora represents the original plant communities of these sites. Plants at the sites were identified and confirmed to be naturally from the general area, using Robinson (1994) and Fairley and Moore (1989). Where species identification was difficult, specimens were confirmed by the Janet Cosh Herbarium, School of Biological Sciences, University of Wollongong.

When examining the vegetation on and around the site, careful note was made of plants growing on the landfilled areas and/or which had recolonised other exposed and degraded areas. These species were targeted as potentially suitable for use in the experimental trials.

General revegetation works in the form of soil testing, amelioration, ripping, fertilising and seeding (mostly with a mix of exotic grasses) had been carried out at each of the sites on completion of landfilling and capping. The main objective of these revegetation works was surface stabilisation and meeting requirements set out for closure by relevant government departments, e.g., NSW Department of Land and Water Conservation (now Department Infrastructure Planning and Natural Resources).

The following sections (2.2.1, 2.2.2, and 2.2.3) describe the three sites used for field experiments, with a focus on factors that may influence the success, or otherwise, of a revegetation program. The information provided in these sections shows how these sites were ideal for this experimentation in that their climate, topography, soils, vegetation and history are similar enough to enable comparison, while their differences provide interest and scope to identify significant limiting factors.

2.2.1 Site 1 - Horsley Park

Site 1 was located at the rear of an operational brick and pipe making clay mine. It has maintained dirt roads, some water retention ponds, a nearby dam, and very little native vegetation in the immediate vicinity of the landfill (Figure 2.2). The landfill comprised

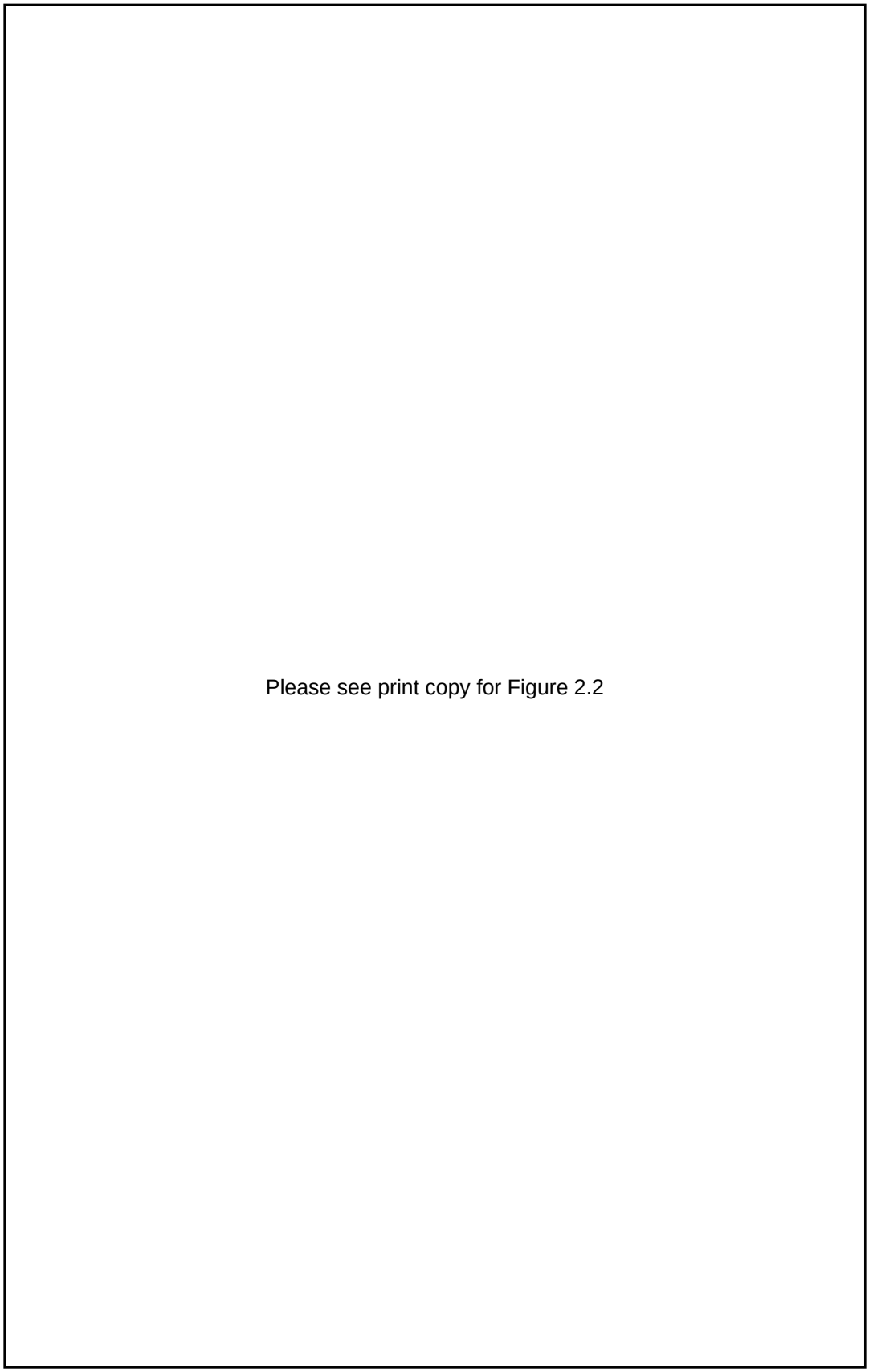


Figure 2.2 Site 1—Horsley Park Map. Contours are those present at the start of the trials.

a single landfilled pit of approximately 3.5 ha. The pit was filled with waste to a mounded surface with slopes ranging from 4H:1V (1 unit vertical lift in 4 units horizontal lengths) and 20H:1V (1 unit vertical lift in 20 units horizontal lengths). Conditions of operation at the site stipulated that the wastes accepted be non-putrescible solid waste, which are non-toxic, non-hazardous and non-odorous. Landfilling ceased in February 1994, with capping completed and initial revegetation works undertaken in April 1994. Additional works, including soil amelioration, sowing of exotic grasses, mulching and additional capping were carried out over the following two years.

No climate data had been recorded at Site 1 prior to my study. During the course of the experiments, I installed a rainfall gauge on the site which was monitored approximately weekly. The closest official weather station was at Prospect Dam (Station 067019). Average annual rainfall at this station is 871.3 mm with higher falls in summer and autumn (Bureau of Meteorology, 2005).

The soils at this landfill were generally clayey, acidic, saline and low in nutrients, typical of this region. A summary of results from five composite soil samples, collected in November 1994, are provided in Table 2.1. These analyses were conducted at a NATA-registered laboratory (Sydney Environmental and Soil Laboratory).

Capping material was obtained from stockpiled heavy clay soil derived from subsoils on the site. Initial revegetation works were carried out in April 1994 with fertiliser applied and an exotic grass mix comprising Coolabah oats (60 kg/h), Victorian rye (20 kg/ha), Wimmera ryegrass (10 kg/ha), Seaton Park (4 kg/ha), White clover (2 kg/ha), and kikuyu (2 kg/ha); plus three *Acacia* species (1 kg/ha each of *A. decurrens*, *A. falcata*, and *A. fimbriata*), sown over the landfilled area. Germination and survival from this revegetation attempt was very low and a new program was undertaken in December 1994, following site examination and soil testing (see Table 2.1).

The revegetation program in December 1994 involved the application of lime and fertiliser (described as high potassium, high phosphorus) at the rate of 4 t/ha and 0.5 t/ha respectively, and the sowing of seed at the rate of 80 kg/ha. The seed mix consisted of Japanese millet (20 kg/ha), couch (16 kg/ha), carpet grass (10 kg/ha), Rhodes grass (6 kg/ha), Wimmera ryegrass (9 kg/ha), hard fescue (4 kg/ha), tall wheat

grass (5 kg/ha), purcinella (5 kg/ha), Palastine clover (2 kg/ha) and Alsike clover (3 kg/ha).

Table 2.1 Summary of initial soil analyses for the three study sites (see Appendix A for full results)

Test	Unit	Site 1 5 composite samples	Site 2 7 composite samples	Site 3 4 composite samples
pH (1:2 in water)		4.5-5.2	4.9-8.6	5.4-6.5
pH (1:2 in $CaCl_2$)		4.1-4.7	4.2-8.0	4.7-5.9
Salinity (1:2 in water, conductivity)	mS/cm	0.7-1.8	0.3-2.7	0.2-0.6
Chloride (1:2 in water)	mg/kg	302-1022	354-1736	-
ECEC (NH_4Cl 1 mol/L pH 6.0)				
Sodium	cmol/kg	1.91-4.08	1.01-2.96	0.62-4.08
Potassium	cmol/kg	0.17-0.29	0.17-0.28	0.07-0.12
Calcium (DL 0.2)	cmol/kg	1.13-6.39	0.61-3.34	BDL-0.20
Magnesium	cmol/kg	6.49-7.12	5.73-10.82	2.98-8.03
Aluminium	cmol/kg	0.57-1.85	0.83-2.31*	0.03*
TOTAL	cmol/kg	12.09-16.57	9.83-15.10	3.95-12.09
Phosphorus (Bray No. 1 acid fluoride extract) (DL 0.8)	mg/kg	BDL	BDL-7.6	BDL
Ammonium (1:2 in 0.01M $CaCl_2$)	mg/kg	14.6-28.6	8.7-22.1	11.5-14.8
Nitrate (1:2 in water)	mg/kg	0.5	0.5-14.7	2.8-4.6
Sulfate (1:2 in water)	mg/kg	92-160	60-203	30-102

*Not analysed for all samples; BDL = Below detection limit

In addition to the application of lime and fertiliser and the sowing of exotic grass mixes, around 40 native shrub and tree species were planted within 20 metres of the landfill perimeter in 1994-5. These plants were indigenous to the Cumberland Plain and largely comprised Melaleuca, Leptospermum and Casuarina species.

Despite these revegetation attempts, at the start of the current research, the landfill site was largely bare with only small patches of grass and a few isolated shrubs.

The remnant vegetation on the site consists of highly disturbed Cumberland Plain Woodland. Disturbance to the vegetation is mostly in the form of past clearing for mining and the presence of roads and tracks. The main tree species were *Angophora floribunda*, *Eucalyptus crebra* and *E. tereticornis*, while the shrub layer included *Bursaria spinosa*, *Daviesia ulicifolia*, *Hardenbergia violacea*, *Indigofera australis*, *Melalauca decora*, *Microleana stipoides*, *Oxlobium scandens*, *Pultenaea retusa*, *P. villosa* and *Themeda triandra*.

Several vertebrates were present at the site including hares (*Lepus capensis*), ducks, masked plovers (*Vanellus miles*), and red-bellied black snakes (*Pseudechis porphyriacus*). Through general site observations and identification of scats and tracks, the only large herbivores present at the site appeared to be hares. No evidence of herbivory of young plants was observed from revegetation carried out on site in 1994.

2.2.2 Site 2 - Schofields

The landfill is located at the back of an operational mine site with maintained roads, some water available and about 70% surrounded by disturbed native vegetation (Figure 2.3). It comprised a single landfill of approximately 6 ha which was filled with waste to a mounded surface with slopes ranging from 4H:1V (1 unit vertical lift in 4 units horizontal lengths) and 20H:1V (1 unit vertical lift in 20 units horizontal lengths).

Like Site 1, Site 2 is located within the lowest rainfall zone of the Cumberland Plain with average annual rainfalls around 900 mm. No weather-recording instruments were present at the site. During the experimental period a rainfall gauge was installed on the landfill and monitored approximately weekly. The closest official weather stations were at Prospect Dam (Station 067019) and Seven Hills (Station 067026). The average annual rainfall at Prospect is 871.3 mm and at Seven Hills 945.1, with higher falls in summer and autumn (Bureau of Meteorology, 2005).

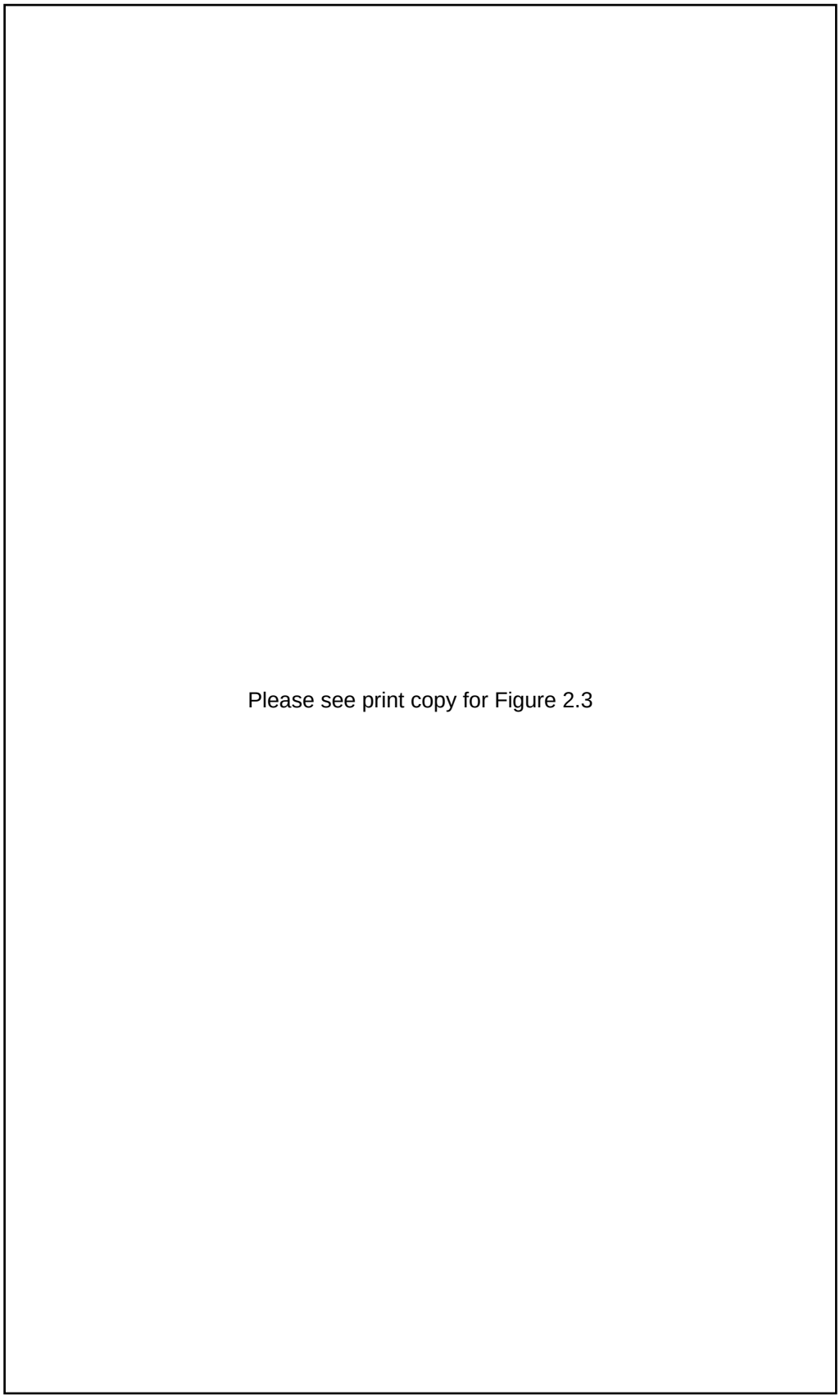


Figure 2.3 Site 2—Schofields Map. Contours are approximate for the time when trials commenced at this site.

The soil analyses (January, February and April, 1995) show that the clay-rich soils at this landfill are typical of those of the area, being generally acidic, saline and low in nutrients (Table 2.1).

The capping material was heavy clay derived from the site and nearby areas. Initial revegetation works were carried out in December 1995 with fertiliser (NPK 11:16:15), lime and gypsum applied at the rates of 0.5, 4 and 4 tonnes/ha respectively. An exotic grass mix comprising Japanese millet (20 kg/ha), couch (16 kg/ha), carpet grass (10 kg/ha), Rhodes grass (6 kg/ha), Wimmera ryegrass (6 kg/ha), hard fescue (4 kg/ha), tall wheat grass (5 kg/ha), and clover (6 kg/ha), was sown on the landfilled area in January 1996. The current research coincided with these revegetation works, and so the landfill site was largely bare when the research started.

The areas of native vegetation to the north-east and north-west had very disturbed understorey from silt movement, the area to the south-east was affected by previous stockpiling and weed infestation and the area to the south was under powerlines with several access roads and tall vegetation pruned. The main tree species in the remnants was *Eucalyptus tereticornis* while shrub species included *Acacia falcata, Bursaria spinosa, Cryptandra spinescens, Dillwynia juniperinai, Dodonaea cuneata* ssp. *cuneata*, *Grevillea juniperina*, *Hardenbergia violacea*, *Melaleuca decora*, *Olearia microphylla*, *Ozothamnus diosmifolius* and *Themeda triandra*.

Vertebrates observed at the site included eastern water dragon (*Physignathus lesueurii*), long-necked turtle (*Chelodina longicollis*), birds and frogs. The only large herbivores known to be present on the site (recorded only from scats) were hares.

2.2.3 Site 3 - Londonderry

This site had previously been mined for brick and pipe-making clay with no operational mining at the time of my studies. At the start of the research, this site was still operating as an active landfill. Once landfilling was completed, the site was landscaped to form undulating domes which blended with the surrounding land. A large stockpile of clay was also present on the site during the experimental period (Figure 2.4). This site is in a more isolated location than

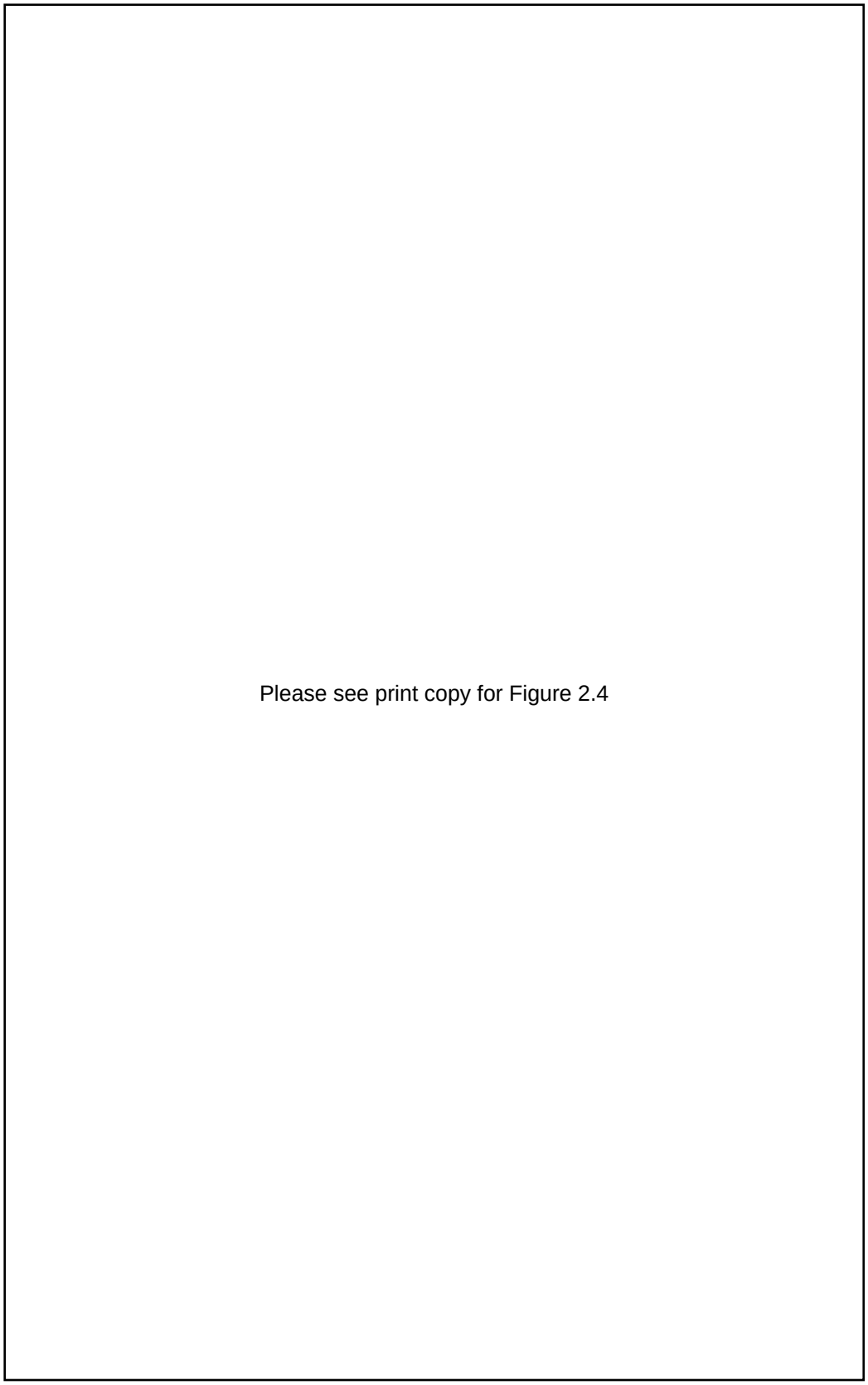


Figure 2.4 Site 3—Londonderry Map. Contours are those at the time that trials started at the site. The stockpile has since been removed.

the other two sites, and had much more native vegetation around it. The surrounding vegetation was also less disturbed.

Londonderry is located near the western edge of the Cumberland Plain with the annual rainfall for the zone around 800 mm per annum. No weather-recording instruments were present at the site at the start of the experimental work. However, during the experimental period, a rainfall gauge was installed on the site and was monitored daily to weekly. The closest official weather station was at Richmond (UWS-Hawkesbury Station 067021), where the average annual rainfall was 801.3 mm per annum, with higher falls in summer and autumn (Bureau of Meteorology, 2005).

The soils at Site 3 were slightly different from the other two sites with the presence of alluvial lenses of sandier material. Analyses (August 1995) of these more silty soils showed they were generally less acidic and less saline than those at Sites 1 and 2 (Table 2.1).

The landfilling was carried out in stages, so too were the capping and revegetation works. The capping material was derived from quarried material on site with no topsoil used. At the start of the research, the site was still an active landfill with no revegetation works completed. As the site was still active, experimental work was undertaken later on, when two areas were completed (capped)(Figure 2.4). Two other areas were completed on the site at this time, they were not used for experiments as one contained specialised wastes and the other was marked for future work. In September 1995, the two areas suitable for experimentation were spread with lime and gypsum at the rates on 1 and 6 tonnes/ha respectively. Fertiliser was also spread at the rate of 500 kg/ha. An exotic grass mix containing Japanese millet, couch, Kangaroo Valley rye, carpet grass, creeping red fescue and white clover, was sown on the areas at the rate of 90 kg/ha.

When experiments were commenced at Site 3 the areas were largely bare with some grass on the two recently completed landfill areas.

The vegetation at Site 3 differed from the vegetation at the other sites in three respects. Firstly, the surrounding vegetation was more extensive; secondly, it was less disturbed with a more developed shrub layer and few weeds; thirdly, the vegetation was also

influenced by the sand lenses in the area and showed characteristics of the Castlereagh vegetation, e.g., the presence of species such as *Angophora bakeri, Banksia spinulosa* and *Pimelia linifolia*.

The main tree species in the area were *Angophora bakeri* and *Eucalyptus parramattensis*, while the shrub layer included *Acacia falcata, Hardenbergia violacea, Hakea sericea, Leptospermum polygalifolium, Lomandra longifolia, L. multifida, Melaleuca nodosa, M. linifolia, Pimelea linifolia* and *Pultenaea villosa.*

Vertebrates observed at the site include eastern grey kangaroo (*Macropus giganteus*), hares, ducks and other birds. Two of these species, hares and grey kangaroos, are major herbivores. Fencing at this site was not complete with free access in and out of the site via bund walls, which formed much of the boundary on the eastern and western sides of the site (Figure 2.4).

2.3 Species selection

The third aim of the research (see Section 1.7) was to identify plant species, which would be suitable for use in the field experiments. This was a very important aspect of the research as there were a number of characteristics that the species needed to possess; for example, low growing stature and ability to grow in similar conditions to those present at the sites (see Section 1.5.4).

As part of the search for suitable species, the vegetation in the areas around the landfill sites was examined for species which were low growing, appeared to thrive in the local conditions, growing in open exposed locations on slopes and those which appeared to be pioneer species (spreading out into open spaces).

Apart from a plants capacity to survive and grow in the conditions present at the sites, Robinson *et al*. (1992) argued that three other criteria should be included: high and rapid reproductive capacity; attractiveness to seed dispersers; and rapid turnover to allow for succession to occur. These factors were also taken into consideration, where known.

In the sections below, each of the criteria used for selecting species is outlined and the resulting species lists examined.

2.3.1 Species selection criteria

The initial list of potential species was identified using the following six criteria:

i. *Indigenous to the Cumberland Plain (see Section 1.5.4)*
For the purpose of this research, this criterion was interpreted as follows: listed as from the Cumberland Plain in the references Robinson (1994) or Fairley and Moore (1989); or presence on, or around, one of the experimental sites (pers. obs.) and known from the Sydney region. The Robinson (1994), and Fairley and Moore (1989) references, were used as they cover the Sydney Region and list the vegetation type where the species are found. The areas examined were the native bushland growing on and around the study sites, and on neighbouring mining areas of similar soil and topography.

ii. *Low growing, maximum height of 2 metres (see Section 1.4.2.3)*
Where there is some reference to a species growing higher than 2 metres, the plant may still be included on the list if it is unlikely to grow taller than 2 metres in the conditions present at the experimental sites. Groundcovers, or species with a spreading habit, were also considered desirable for erosion control.

iii. *Lack of taproot*
Due to the concerns relating to the possible impact of plants on the cap (see Sections 1.4.2.3 and 1.6); species known to have a taproot, or large woody root system, were excluded from the list of potential species. For most species examined, information on the root systems were not known. As such, this information was not required for a species to be listed as potentially suitable.

iv. *Species known to grow in heavy clay and/or low permeability soils*
On the whole, both the capping and cover soil for the three study sites comprised heavy clay, low permeability soils (Section 2.2). For many species the ability to grow in heavy clay soils was met through the first criterion, indigenous to Cumberland Plain or growing on or around one of the

experimental sites. However, some areas of the Cumberland Plain and Site 3 are not comprised of heavy clay. Additionally, Arthur *et al*. (1981), found that species naturally tolerant of flooded soils with low oxygen content, were more tolerant of landfill gas in the soil; as such, if landfill gas is present, then species known for growing on the poorly drained, heavy clay soils of the Cumberland Plain, may also have a better chance of survival.

v. *Able to grow in dry, open conditions (see Sections 1.4.1. and 2.1.1)*
Either a reference to the plant growing in dry, open conditions, being drought tolerant; or observed growing in open conditions on and around the experimental sites.

vi. *Rapid growth rate*
Quick coverage was desirable for erosion control and aesthetics. Growth rate was not always known for the species examined and is not essential for a plant to be successfully established. As such, this was a desirable factor, and not required for a species to make it on to the list of potential species.

Application of these search criteria produced 59 potential target species (Table 2.2). This list was refined to the final list of species for use in the experiments using the more specific criteria described in Section 2.3.2.

2.3.2 Refining the species search

The first part of refining the list was availability of plant material. For 20 of the 59 potential species identified, seed was readily available through commercial seed suppliers: *Acacia elongata, A. linifolia, A. ulicifolia, Atriplex semibaccata, Bursaria spinosa, Chrysocephalum apiculatum, Daviesia genistifolia, D. ulicifolia, Danthonia* sp., *Dillwynia juniperina, Hardenbergia violacea*, *Indigofera australis, Kennedia rubicunda*, *Lomandra longifolia, Melaleuca erubescens, M. thymifolia, Microleana stipoides, Ozothamnus diosmifolius, Pultenaea villosa* and *Themeda triandra*. An additional species was available at the species, and not the subspecies, level, *Dodonaea viscosa.* Another species, *Calotis cuneifolia,* had seed readily available at Site 2. This gave a list of 22 available species.

Table 2.2 Potential experimental species and their properties (see Section 2.3.1)

Please see print copy for Table 2.2

The species finally selected for use in the experiments were identified from the refined list above by revisiting the criteria set out in Section 2.3.1. More focus was placed on the species being present at one of the experimental sites and having rapid growth and/or reference to the species as a primary coloniser. In addition, the species should be readily germinated and grown, e.g., not known to be very difficult to germinate.

For a species to be included, it did not have to meet all of these criteria, and indeed this information was often not known. Rather, I weighed up of all the available information and chose species that best represented the desirable characteristics, while ensuring that the resultant list of species represented a range of families and various seed types. More weight was given to those species found at Sites 1 and 2 rather than Site 3 (Londonderry), because the climate, topography and soils at Site 3 were slightly milder, with higher rainfall, lower slopes and less saline soils. As such, plants growing in open conditions at Site 3 would be growing in relatively easier conditions than those growing in an equivalent location at Sites 1 and 2.

From the criteria discussed, 17 species were selected for use in the experimental trials: *Acacia linifolia*, *A. ulicifolia*, *Atriplex semibaccata*, *Bursaria spinosa*, *Calotis cuneifolia*, *Chrysocephalum apiculatum*, *Danthonia* sp., *Daviesia genistifolia*, *D. ulicifolia*, *Dillwynia juniperina*, *Hardenbergia violacea*, *Indigofera australis*, *Kennedia rubicunda*, *Lomandra longifolia*, *Melaleuca thymifolia*, *Ozothamnus diosmifolius* and *Themeda triandra.* These species span 15 genera and 8 families with a range of different seed types (Table 2.3). Information on seed treatment and germination relevant to these species is provided in Section 2.3.3.

Due to time, material, and financial constraints, not all species were used in every experiment.

Table 2.3 Base information about the target species (see Section 2.3.3)

Species	Family	Seed description	Source
Acacia linifolia (Vent.) Willd.	Mimosaceae	Seed in pods, tough coat, elaiosome, 2.7 g/100 seed	Commercial, 3 batches
Acacia ulicifolia (Salisb.) Court	Mimosaceae	Seed in pods, tough coat, elaiosome, 1.67 g/100 seed	Commercial, 2 batches
Atriplex semibaccata R.Br.	Chenopodiaceae	Berries, soft, 0.42 g/100 seed	Commercial, 1 batch
Bursaria spinosa Cav.	Pittosporaceae	Seed in papery pods, flat, light	Commercial, 2 batches + Site 1
Calotis cuneifolia R.Br.	Asteraceae	Spurred	Site 2
Chrysocephalum apiculatum (Labill.) Steetz	Asteraceae	Seeds achenes with pappus, small, light,	Commercial, 1 batch
Danthonia sp.	Poaceae	Seeds a grain with awn	Commercial, 1 batch
Daviesia genistifolia A.Cunn. ex Benth.	Fabaceae	Seed in pods, kidney shaped, tough coat, small	Commercial, 2 batches
Daviesia ulicifolia Andrews	Fabaceae	Seed in pods, kidney shaped, tough coat, small	Commercial, 2 batches
Dillwynia juniperina Lodd	Fabaceae	Seed in pods, kidney shaped, tough coat, small	Commercial, 2 batches
Hardenbergia violacea (Schneev.) Stearn	Fabaceae	Seed in pods, kidney shaped, tough coat, elaiosome	Commercial, 3 batches
Indigofera australis Willd.	Fabaceae	Seed in pods, cylindrical, tough coat; 0.33 g/100 seed	Commercial, 2 batches
Kennedia rubicunda Vent.	Fabaceae	Seed in pods, kidney shaped, tough coat, elaiosome	Commercial, 3 batches
Lomandra longifolia Labill.	Xanthorroeaceae	Seed in papery seed capsules; 1.33 g/100 seed	Commercial, 3 batches
Melaleuca thymifolia Sm.	Myrtaceae	Seed in woody capsules, fine	Commercial, 2 batches
Ozothamnus diosmifolius (Vent.) DC.	Asteraceae	Seed achenes with pappus,	Commercial, 1 batch + Site 2
Themeda triandra (R.Br.) Stapf	Poaceae	Seeds a grain with awn	Commercial, 1 batch

Table 2.4 Seed treatment and base germination for the target species (see Sections 2.3.2 and 2.3.3)

Species	Batch	Source*	Batch weight (grams)	Number of seeds per gram
Acacia linifolia	B1	Commercial: MLF	25	35
	B2	Commercial: HSC	55	41
	B3	Commercial: ASC	600	36
Acacia ulicifolia	B1	Commercial: MLF	25	90
	B2	Commercial: ASC	25	85
Atriplex semibaccata	B1	Commercial: ARC	500	235
Bursaria spinosa	B1	Commercial: MLF	50	830
	B2	Commercial: HSC	50	-
Calotis cuneifolia	B1	Site 2	-	900
Chrysocephalum apiculatum	B1	Commercial: ASC	10	30500
Daviesia genistifolia	B1	Commercial: ASC	100	150
	B2	Commercial: ASC	6	150
Daviesia ulicifolia	B1	Commercial: ASC	55	150
Dillwynia juniperina	B1	Commercial: ASC	10	125
	B2	Commercial: ASC	10	132
Hardenbergia violacea	B1	Commercial: MLF	25	41
	B2	Commercial: HSC	50	35
	B3	Commercial: ASC	500	
Indigofera australis	B1	Commercial: MLF	25	188
	B2	Commercial: ASC	150	
Kennedia rubicunda	B1	Commercial: MLF	25	45
	B2	Commercial: HSC	55	51
	B3	Commercial: ASC	500	50
Lomandra longifolia	B1	Commercial: MLF	25	83
	B2	Commercial: HSC	25	81
	B3	Commercial: ASC	300	140
Melaleuca thymifolia	B1	Commercial: MLF	10	30000 [MLF]
	B2	Commercial: HSC	25	-
Ozothamnus diosmifolius	B1	Site 2	-	18180
	B2	Commercial: HSC	10	-
Themeda triandra	B1	Commercial: MLF	25	-

ASC =Australian Seed Company; ARC = Australian Revegetation Corporation; HSC = Harvest Seed company; MLF = M L Farrer.
** Number of seeds in a tray rather than a punnet

Treatment	Conditions No. of seeds per punnet; temperature	Number of replicates	First germination (days)	Last germination (days)	Germination rate (%)	Seed batch
BW	50; 25°C	-	14	62	77.0	Al-1
BW		-	6	35	55.5	Al-2
BW	50; 15°C	8	5	76	83.3	Al-3
BW	100**; 25ºC	5	21	80	37	Au-1
BW	100**; 25ºC	5	6	35	5	Au-2
None	50; 25ºC	4	6	18	52	As-1
None	50; 25°C	4	20	-	27	Bs-1
BW	50; 15°C	8	n/a	Nil after 74	0	Bs-2
None	50; 25°C	8	6	83+	62.3	Cc-1
None	100**; 25ºC	5	8	15	13	Ca-1
BW	50; 25°C	8	10	100	35	Dg-1
BW	50; 25°C	8	6	35	41.5	Dg-2
BW	50; 15°C	7	14	139*	92.9	Du-1
BW	50; 25°C	4	10	100	61.0	Dj-1
BW	50; 25°C	4	6	35	15.5	Dj-2
BW	100**; 25°C	5	7	67	39	Hv-1
BW	50; 25°C	4	6	-	-	Hv-2
BW	50; 15°C	8	6	247	76.3	Hv-3
BW	100**; 25°C	5	-	-	65	Ia-1
BW	50; 15°C	8	-	-	-	Ia-2
BW	100**; 25ºC	5	6	48	40	Kr-1
BW	50; 25ºC	4	6		42	Kr-2
BW	50; 15°C	8	4	95	66.5	Kr-3
None	100**; 25ºC	5	43	-	59	Ll-1
None	50; 25°C	4	-	-	47	Ll-2
None	50; 25°C	8	n/a	Nil after 83	0	Ll-3
None	0.05 g; 25ºC	5	22	126	-	Mt-1
None	0.05 g; 15ºC	8	6	166+	-	Mt-2
None	100**; 15ºC	8	n/a	Nil after 60	0	Od-1
None	0.05 g; 25ºC	8	n/a	Nil after 83	0	Od-2
None	100; 25°C	5	13	-	20	Tt-1

2.3.3 Seed treatment and germination

Numerous factors affect seed germination, including seed age, quality, storage, exposure to light, moisture, seed coat and dormancy (Beardsell & Richards, 1987; Blombery & Maloney, 1994). Therefore, germination tests were carried out for each batch of seed. I did this even where results on the treatment and germination of a particular species had been reported in the literature, because the dormancy may be affected by storage, and by the area from which the seed is collected (Blombery & Maloney, 1994).

Many of the species required treatment of the seeds to overcome dormancy. One of the most common methods of treatment for seeds with hard coats is the use of near-boiling water, with the seed left to soak for several hours (e.g., Elliot & Jones, 1989). Other methods of scarification, such as, mechanical scratching may be used; however, the boiling water treatment is easy to replicate and to use on large volumes of seed, as would be the case in a full-scale revegetation program. Water was brought to the boil, allowed to cool to around 95°C, and then poured over the seeds so that they were immersed by at least 10 times their volume. The seeds were left to soak, then drained and either used immediately, or spread out on absorbent towelling to dry, as required.

From initial examination of the literature available, there was conflicting information on the need for treatment of seed prior to sowing and/or the type of treatment required for a few of the target species. If treatment was not necessary for germination, then none was used. Germination was tested on each batch of seed for each of the species to confirm that the seed obtained was viable and to check germination rates for the treatment regime proposed (Table 2.4).

For each of the experiments, germination controls were used. In the case of field-based experiments, seeds from the same batch and age were treated in the same way and sown in vermiculite perlite in the laboratory. Details of each of the germination controls are provided in the methods sections of the following chapters.

For some species, the germination rate in the treatments was low (*Bursaria spinosa*, *Chrysocephalum apiculatum*) or even zero (*Ozothamnus diosmifolius*). These species were still used in the field experiments because so little is known about them and it was possible that conditions in the field would be more conducive for germination. In

addition, the field experiments were run for up to one year, and for some species, time may be all that is required.

As discussed above, for most of the species used in the experiments, there was little to no base information known about their germination, either in controlled conditions, or in the field. In addition there was no information available on the germination of these species at the experimental sites. Therefore, the next stage of this study was to undertake pilot studies at two of the experimental sites to determine the germination and growth of these species. These pilot studies would also provide information on the number of species and seeds required and the presence and degree of herbivory.

Chapter 3
Preliminary germination and growth studies

3.1 Introduction

Each of the species proposed for use in this research is known to grow in the area where the landfills were situated. There was little to no information available, however, on the germination and growth of these species, either in controlled conditions or in the field. The aim of this chapter, therefore, is to describe and discuss a series of germination and planting studies undertaken to determine germination time and rate (Sections 3.2 and 3.3), and growth and survival rates (Section 3.4), of the experimental species in the conditions of the landfill environments. As there was limited information available about the species, these pilot studies were designed to be progressive in nature, so the results of each stage could be incorporated into the design of the next. It is important to note that the aim of these pilot studies was not to provide direct comparison between the sites, or to provide answers to specific research questions; rather, it was to identify possible limiting factors and, therefore, what questions needed to be asked.

Growth and survival of plants in the landfill environs is required for soil stability, dust suppression and aesthetics. In addition, where indigenous species are wanted in the long-term vegetation plan for a site, it is essential that the plants reproduce successfully. Consequently, observations were made throughout the study on the presence of flowers, fruits and mature seeds. Seeds from plants grown as part of any of the studies were collected and tested for germination as per the methods in Section 2.3.3. The results are included with those of the relevant study or experiment. This part of the research was facilitated by much of the work being carried out part-time over several years, enabling the observation of some plants from seeds, to seedlings then maturity and reproduction.

3.2 Field germination Pilot study I: Site 1

3.2.1 Introduction

Field germination Pilot study I, was installed at Site 1 in February 1995, after the area had been sown with a mixture of grass seed and ameliorated with lime and fertiliser as part of general revegetation works (see Section 2.2.1). The aims of this pilot study were to test the germination rate of some of the experimental species under the site conditions, and to determine the extent of seedling herbivory by hares (*Lepus capensis*) and/or rabbits (*Oryctolagus cuniculus*). This second aim was addressed in the pilot study by an exclosure study with fenced (to exclude rabbits and hares) and unfenced plots. However, this part of the experiment failed, because of the unexpected presence of horses, which walked over the fences and knocked them down within weeks of sowing. These horses came from a neighbouring property through a damaged boundary fence. As a result of the damage, no comparison could be made between the fenced and unfenced areas, so, except for describing the experimental design and reporting general observations, this part of the study will not be discussed further.

3.2.2 Materials and methods

Five, 5 m^2 quadrats (1 m x 5 m) were sown at the rate of 1 g/m^2 with: *Hardenbergia violacea* (batch Hv-1); *Kennedia rubicunda* (batch Kr-1); *Bursaria spinosa* (batch Bs-1); *Themeda triandra* (batch Tt-1) and *Danthonia* sp.; and no additional seed. For seed treatment and base germination rates refer to Table 2.4. The no additional seed quadrat was treated the same way as the other quadrats without the addition of experimental species. These no additional seed quadrats provided a comparison of the vegetative growth and percent cover of the grass cover crop, without the study species present.

The quadrats were 1 m wide to ensure that every part of the quadrat was accessible without walking on or otherwise trampling any part. The quadrats were 5 m long so that there were 5, 1 m^2 areas that could be destructively sampled at different time intervals. This part of the pilot study did not proceed due to very low germination and survival and no further description is provided. The quadrats in the plots were lined up along the slope so seed movement under the influence of rain and/or gravity would not result in seeds running onto an adjacent quadrat (see Figure 3.1).

The fences were constructed from 1 m wide chicken wire supported by metal posts (star pickets) at 3-3.5 m intervals (see Figure 3.1). As recommended by Bhadresa (1986), part of the wire was buried to prevent rabbits and/or hares from burrowing under the fence. Bhadresa (1986) recommended 0.5 m of the wire netting be buried in a trench outside the plot; allowing for local conditions and the recommendations of the supplier, 0.2 m of the netting was buried in this pilot study. No burrowing under the fenced was observed either during or after the pilot study. Metal posts were also used to mark the corners of the unfenced plots. Wooden stakes were used to mark the corners of the quadrats and string was run between the stakes to mark the sides.

Site 1 is a relatively flat topped hill with five different topographic areas: top gradual slope, north facing slope, east facing slope, south facing slope and west facing slope (Figure 2.2). One plot was randomly placed within each of these five topographic areas using a random number generator and a number of limitations. The limitations were that each plot be: located on a similar slope; entirely within the section nominated; and at least 2 m away from other site structures (e.g., monitoring wells, fences).

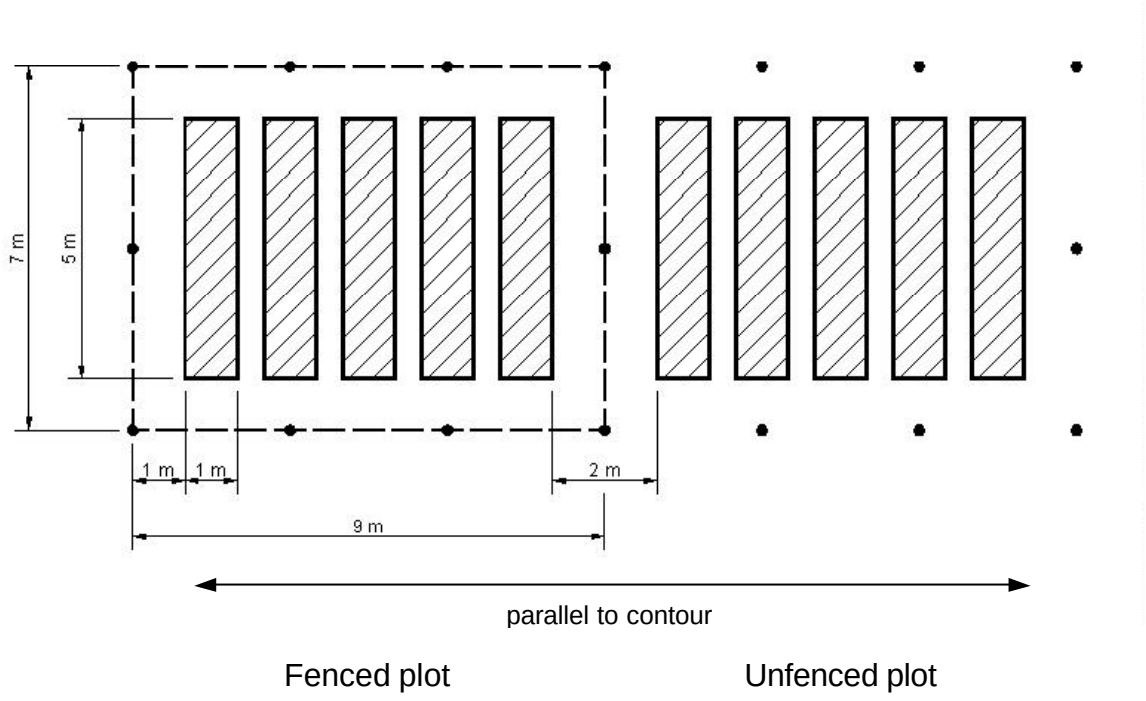


Figure 3.1 Field germination Pilot study I, plot set up

The plots were monitored for four months, fortnightly for the first four monitoring occasions, then a further three at three-week intervals. The plots were then monitored again at 11 and 18 months. A 1 m^2 area was monitored in each of the quadrats. The number of seedlings of the target species was recorded on each monitoring occasion. Where there were no seedlings in the monitored area, the entire quadrat was quickly examined to see if there were any seedlings from the trial species.

3.2.3 Results

The germination rate from this pilot study was very low. The only two study species to show germination were *K. rubicunda* and *H. violacea*, with 0-1 seedlings per m^2. Based on the number of seeds per gram (see Table 2.4), this represents a percentage germination of less than 5%. With such low germination rates in the monitored area, the entire 5 m quadrats were scanned for seedlings with the same results. The 4 month survival of the seedlings was less than 1% for *K. rubicunda* and *H. violacea*, with a total of 4 surviving seedlings for each species across all plots. In contrast, the base germination percentages of these species were *H. violacea* 75% and *K. rubicunda* 60% (Table 2.4).

Herbivory appeared to be one of the causes of seedling loss as some of the seedlings disappeared with no stems remaining, and some had their tops removed. As already described, horses were present during this pilot study, and hares and rabbits were known to be on the site. Insects may also have been responsible for this type of damage, small holes in leaves were attributed to insects.

No germination was observed in the pilot study for *B. spinosa*. This can easily be explained through two mechanisms: firstly the base germination of this species has been low (Table 2.4); and secondly the conditions in the field, e.g., hot and dry with saline soil.

The grasses *Themeda triandra* and *Danthonia* sp. may have shown germination in this pilot study, but identification of the seedlings in the field proved to be very difficult, with other grasses present from the general revegetation works at the site. It would be very useful to know the germination performance of these native grass species in the landfill condition, but, due to the difficulty of identification, this was beyond the scope of the current research.

As mentioned above, the presence of horses, in both treatments, made it impossible to statistically compare the fenced and unfenced areas. In addition, the very low field germination rates also prevented statistical comparison. It is interesting to note, however, that 11 months after sowing there were ten surviving seedlings, seven *K. rubicunda* and three *H. violacea*, five in the fenced plots that were still intact and five in the unfenced plots. After 18 months, however, there were six surviving seedlings, four *K. rubicunda* and two *H. violacea*, only one of which was in the unfenced plots.

3.2.4 Discussion

With such low germination rates, more seeds need to be used for each species. More species should also be used to assess if the low field germination rates are across a range of geneses and species. With high site variability, more replicates are also required.

There are many possible causes of the low germination. Poor seed viability; inadequate soil moisture from low rainfall during some periods; other soil factors - either physical and/or chemical; herbivory of seedlings; and removal by seed predators such as birds or ants. Soil factors which may have influenced the low germination rates observed include: high bulk density, surface sealing, low permeability, and soil chemical characteristics, e.g., relatively high salinity (see Section 2.2.1).

The soils on the sites were generally high in exchangeable aluminium (see Sections 2.2.1 and 2.2.2, and Table 2.1). There are many examples in the literature of the affects of aluminium toxicity on a variety of plants (e.g., Massey, 1972; Berg & Vogel, 1973; and Wild, 1993). Gemmell (1977) also describes how aluminium in soils with low pH can reduce the amount of available phosphorus. While the species chosen do grow in the local soils, which are naturally high in aluminium, the seeds for the plants were sourced from further afield and, through variations in local genotypes, it is possible that the plants grown were not able to survive in the local active aluminium conditions. The same is true for any other factor at the site.

In the four months after sowing there were 176 mm, 25 mm, 152 mm and 22 mm of rainfall recorded at the closest station (067019; Bureau of Meteorology, 2005). Having good falls of rain followed by periods dry could easily result in poor seedling survival, but, should not result

in poor germination. However, good rainfall was often proceeded by hot dry conditions, which could have resulted in newly emerged seedlings dying before being counted. Site conditions were dry in the 5th and 6th months from sowing with 1.4 and 0 mm respectively. With no additional watering, these dry conditions would have affected both seedling survival and ongoing germination.

Five months after sowing the pilot study, several seedlings of *H. violacea* and *K. rubicunda* were observed near two of the plot areas (Plots 2 and 5). Notably, two seedlings were adjacent to, or higher than, the plots, indicating that the seeds could not have been moved by rainfall or runoff. It is unlikely that the seeds were moved by wind as they were fairly large, not wind dispersed, and were covered with soil at the time of sowing. At Site 1 there was a lot of ant activity and nests readily apparent around the landfilled area; however, few were observed on the landfilled area where the plots were located. The other potential source of seed removal is by birds or small mammals. With evidence for seed movement and the presence of potential seed predators at the site, the importance of seed removal was examined further as part of future experiments (see Section 4.4).

The presence of horses had the potential to seriously impact upon further experiments carried out at the site. The horses were removed from the site, and the fence where they had gained access was repaired.

One plant from this pilot study, from the species *K. rubicunda*, survived to produce seeds. In November 1996, 21 months after sowing, 15 pods were collected from this plant and 60 seeds tested for germinability. The seeds were treated with boiling water and sown in 5 batches of 12 seed on 50:50 vermiculite:perlite as per the other base germination (Table 2.4). The resultant germination was 85%, which was higher than the base germination for the batches of purchased seed (Table 2.4).

This germination pilot study at Site 1 provided some indicators of the limiting factors for germination and survival of species in this environment. The second germination pilot study, at Site 2, incorporated these results in a modified design in an attempt to achieve higher germination.

3.3 Field germination Pilot study II: Site 2

3.3.1 Introduction

This second germination pilot study was installed at Site 2 in May 1996. The aims of this pilot study were: to test the germination of target species at a second site, to test a modified trial design to take into consideration the results of Pilot study I at Site 1, and to compare the general germination rates with those found at Site 1 (see Section 3.2). A general comparison of the experimental design used in field germination Pilot studies I and II is provided in Table 3.1.

Table 3.1 Comparison of field germination Pilot studies I and II

Germination Pilot study I: Site 1	Germination Pilot study II: Site 2	Reason
Fenced and unfenced plots	Unfenced plots	Fencing was not found to be effective
5 plots	10 plots	High site variability
Quadrats 5x1 m	Quadrats 1x1 m	Monitored area was the same in each case
Single species plots	Multiple species plots	With low germination more species need to be tested
5 species tested	11 species tested	Test more species
	Increase in the rate of seed used	Low germination rates observed in Pilot study I
Seed installed per gram	Seed counted	More precise comparison. Equal numbers of seed used for most species

3.3.2 Materials and methods

Direct seeding Pilot study II contained ten 1 m^2 quadrats with seeds from 11 species: *Acacia linifolia* (batch Al-1), *A. ulicifolia* (batch Au-1), *Atriplex semibaccata* (batch As-1), *Bursaria spinosa* (batch Bs-1), *Daviesia ulicifolia* (batch Du-1), *Dillwynia juniperina* (batch Dj-1), *Hardenbergia violacea* (batch Hv-2), *Indigofera australis* (batch Ia-1),

Kennedia rubicunda (batch Kr-2), *Lomandra longifolia* (batch Ll-1) and *Melaleuca thymifolia* (batch Mt-1). For seed treatment and base germination rates refer to Table 2.4. One hundred seeds per species were sown in each quadrat, with the exception of *M. thymifolia*, which due to its small size, had 0.1 g of seed sown per quadrat. Two quadrats were randomly located on each of the five main areas (top, northwest, southwest, southeast, northeast; Figure 2.3) enabling a range of slopes, aspects, and soil types to be included to allow for variation in the site conditions.

Each quadrat was marked using a wooden stake with flagging tape attached. The corners of each quadrat were marked with metal pegs with flagging tape tied on.

Prior to sowing, the quadrats were raked to remove excess vegetation and to break up the soil surface. It should be noted that, for most of the quadrats, there was little to no vegetation present at the start of the study.

On each monitoring occasion, the number of seedlings for each species was recorded (Sheet B1, Appendix B1). The total number of seedlings for each quadrat was also recorded, to include any unidentified seedlings. The quadrats were monitored for five months, when further earthworks were carried out at the site.

3.3.3 Results

Field germination was highly variable, both between species and between quadrats. Average germination percentages across the 10 quadrats ranged from 0% in five species to 4.1% in *Atriplex semibaccata* as follows: *Acacia linifolia* 3.7; *A. ulicifolia* 0; A*triplex semibaccata* 4.1; *Bursaria spinosa* 0; *Daviesia ulicifolia* 0.4; *Dillwynia juniperina* 1.3; *Hardenbergia violacea* 2.7; *Kennedia rubicunda* 2.3; *Indigofera australis* 0; *Lomandra longifolia* 0; and *Melaleuca thymifolia* 0. Total number of seedlings per quadrat ranged from 2 to 37, with an average of 14.5.

Seedling survival over the 5 months was much less than total number of seedlings. Average seedling survival after 5 months for each of species that showed some germination was: *Acacia linifolia* 1.2; A*triplex semibaccata* 2; *Daviesia ulicifolia* 0.2; *Dillwynia juniperina*

0.8; *Hardenbergia violacea* 0.6; and *Kennedia rubicunda* 1.3. The total number of seedlings surviving per quadrat ranges from 0 to 17, with an average of 6.

Herbivory and low water availability appeared to be factors affecting germination and 5 month seedling survival. During a dry spell, some seedlings, especially the *A. linifolia*, were observed as being droopy, as though suffering from water stress. Low rainfall cannot be the only limiting factor, however, as germination did occur in some of the quadrats.

Herbivory on seedlings, in the form of chewed leaves, was observed in four of the quadrats (2a, 2b, 3b and 4b). If seedlings were removed completely this would only be picked up through a decline in the number of seedlings without the presence of dead seedlings being recorded. Hollowed seeds were found in four of the quadrats (1a, 2a, 3a and 5b), it is possible that this also occurred at other quadrats. Therefore, at least part of the low germination rate can be explained by seed predation.

3.3.4 Discussion

As for Pilot study I, the germination rates from this study were very low, though highly variable between species and quadrats. The interspecies variability highlighted the need for using a range of species and the importance of not drawing conclusions from just a few species.

During the course of ongoing site works several areas of the site were mulched using a hydromulch technique and straw. Three of the quadrats, 3a, 3b and 4a, were all mulched. This allowed the opportunity to compare the germination and seedling survival at these quadrats with the un-mulched quadrats. Germination and seedling survival were both more than 3 times higher in the mulched quadrats with the average germination and seedling survival after five months as follows: mulched quadrats germination 28.0, seedling survival 12.0; un-mulched quadrats germination 8.7 and seedling survival 3.4.

Low soil moisture, herbivory and seed predation would appear to be limiting factors for the low germination and seedling survival rates observed. Other soil factors may also contribute. Future germination trials tested the importance of soil moisture (Section 4.3) and seed herbivory (Section 4.4) on germination rates.

3.4 Planting experiment: Sites 1 and 2

3.4.1 Introduction

The first aims of this experiment were to test the growth and survival of species planted across two landfill areas, Sites 1 and 2. Growth and survival were to be examined overall as well as comparing and contrasting between sites, species and planting areas.

3.4.2 Materials and methods

3.4.2.1 The plants

For each species, 14-17 plants were planted in five areas at each of the two sites, Site 1 and Site 2. The planting areas were randomly located in each of the five topographic areas of the sites: top, north, south, east and west at Site 1 (see Figure 2.2); and top, north-west, south-west, south-east and north-east at Site 2 (see Figure 2.3).

The species used at Site 1 (the number planted per area; and per site) were: *Acacia linifolia* (16; 80); *Atriplex semibaccata* (16; 80); *Daviesia genistifolia* (14; 70); *Indigofera australis* (16; 80); *Kennedia rubicunda* (17; 85); and *Lomandra longifolia* (15; 75). Plants of *Dillwynia juniperina* were also available, however, they were slightly droopy with some browning foliage. Two areas (top and west) were planted to test these *D. juniperina* plants; all but one died within two months, so no more of these plants were used.

Site 2 was planted after Site 1 and a different mix of species was used to incorporate the initial results found. Two species were removed, *Daviesia genistifolia* and *Dillwynia juniperina*, and one species added, *Acacia ulicifolia*. The species mix at Site 2 was, therefore, as follows*: Acacia linifolia* (15; 75); *A. ulicifolia* (15; 75); *Atriplex semibaccata* (14; 70); *Indigofera australis* (14; 70); *Kennedia rubicunda* (16; 80); and *Lomandra longifolia* (15; 75). Nineteen plants of *Bursaria spinosa* were also available for use at the time of planting. While not enough for a trial, they were planted in the same areas using the same methods so they would be available for observation and future experiments.

Most of the plants used in the experiments were grown from seed germinated in a shadehouse in trays of 50:50 vermiculite:perlite. Seedlings were then potted into square tubes (50 mm

wide, 125 mm deep) using a commercially prepared soil for Australian native plants. Into the soil I incorporated a low phosphorus fertiliser, with an NPK ratio of 17.0:1.6:8.7 (Osmocote^{TM}). The pots were placed on mesh benches in the shadehouse until the plants were ready. Once grown, the plants were moved out of the shadehouse to acclimatise for at least two weeks prior to planting.

3.4.2.2 Measurement of plant growth and survival

Plants were monitored every 4 to 6 weeks (Sheet B2, Appendix B). On each monitoring occasion, the following information was recorded for each plant: plant identification number, plant size, degree of herbivory, health, and other observations. An outline of each of these characteristics, and how they were recorded, is provided below.

Plant identification number

A label was drawn up for each plant, which contained the initials of the species, the initials of the site and a 3 digit number specific to that species and individual plant. For example, HP Ll 510, refers to Horsley Park Site (Site 1), *Lomandra longifolia*, and 510 is from the top planting area at Site 1 which had plants from 500-516. The words "Uni of Wollongong" were also written on each of the tags to assist others on the sites with identification and hopefully minimise human interference. The tags were white horticultural labels attached with green plastic twist tie and marked with flagging tape.

Size

Recorded as height from ground surface, maximum width, then width perpendicular to the maximum and at the same height. For the groundcovers, *H. violacea* and *K. rubicunda*, the size was recorded by measuring the longest three stems. The size measurements allowed plant growth to be recorded over time and also provided an indication of herbivory.

Grazing

Grazing was recorded using a 6 point scale:

0 – No discernible herbivory;

1 – Tip/s removed;

2 – Holes in and/or around leaves;

3 – "Large amounts' of the plant removed;

4 – Plant grazed to base or felled at or near base;

5 – Plant trampled.

This was meant to be a qualitative scale to give a guideline as to whether herbivory was occurring, and if so, to what degree. As such, no clear boundaries were defined between some of the criteria, e.g., 1 and 3. It was also possible for a plant to score two different points on the grazing scale: e.g., 1 and 2.

Plants continued to be monitored for a period of time after receiving a rating of 4 or 5 to check if regrowth occurred. It is expected that as the plants get older they are more likely to survive a rating of 4 or 5, as over time the root system of the plant will grow and provide storage material. It is also expected that repeated heavy grazing and/or trampling will decrease the likelihood that the plants will survive.

Health

Health of each plant was recorded using a 6 point scale:

1 – Healthy, bright green firm leaves, often new growth present;

2 – As for category one but with droopy tips or slightly off colour;

3 – Paler green foliage with wilting;

4 – Plant browning off;

5 – Apparent death, plant brown;

6 – Plant previously recorded as category 5, new growth now present.

The aim of the health category was to provide a guide for comparison of the species and as an indicator of how the plants were doing. Observations varied between the species, e.g., *I. australis*, tended to drop leaves and leaves yellowed, *K. rubicunda* tended to droop. Monitoring of plants was continued after being given a rating of 5. While the above ground growth is brown and appears dead, there may be still living tissue within the stem or roots which may grow back if the conditions allow. As with the grazing category, it is a qualitative scale with no clear boundaries.

Other

This included: the presence of reproductive structures, e.g., buds, flowers, pods; the presence of herbivores or their scats or tracks; or the presence of insects on the plant.

3.4.2.3 Ground preparation

Prior to planting, the planting areas were ripped using a single tyne ripper to a depth of 300 mm at Site 1 and 400 mm at Site 2. It was not necessary to install rip lines specifically for the planting at Site 2, as the area had been cultivated prior to the planting at this site (see Section 2.2.2). The purpose of ripping was to break the compaction allowing water infiltration and root penetration. Ripping has been shown to increase root growth and plant survival on compacted soils (see for example Ashby, 1997; Yates *et al*., 2000). The problem with planting along a single rip line is that the roots can tend to grow along the rip lines making the plants vulnerable to toppling (Venning, 1988). Soil disturbance created by the ripping, however, results in increased permeability, water holding capacity and soil oxygen. As the plants used in my study were shrubs and groundcovers, the risk of the plants being toppled was minimal. Many authors recommend that the rip lines be installed 0.5 to 1 m in depth (e.g., Venning, 1988; Buchanan, 1989). On capped landfill sites, the ripping depth is dictated by the depth of the cover material. The cap must not be penetrated as this may facilitate the penetration of water into the landfill and the movement of landfill gas into the root zone.

The main alternative to ripping was the installation of individual planting holes. One of the disadvantages to drilled holes is that the sides of the hole can be polished and compacted by the auger, making it difficult for the roots to penetrate outside the planting hole. Rip lines provide a trench of tilled material for the plants to grow along and when installed along the slope can catch water, soil, seed and fertiliser run-off in the event of rain. Rip lines are also cheaper and quicker to install than individually drilled holes.

3.4.2.4 Planting

Planting was undertaken using Hamilton Tree Planters™. These planters were used as they make a hole the same size as the pot, they are quick and easy to use and form a consistent

hole ensuring the plants were installed in the same way for ready comparison. Each hole was made in the centre of a rip line. Then all vegetation within a 0.1 m radius of the hole was removed and vegetation to a radius of 0.2 m was clipped with shears to ground level. One teaspoon (5 g), of long life fertiliser NPK 17.0:1.6:8.7 (Osmocote^{TM}) was placed in the bottom of the hole. The hole was then filled with water and left for 30 minutes prior to planting. When planting, the pot was loosened from the soil and roots, then removed. Basic observations on the size and shape of the root system were made. The soil and root ball was placed in the hole so that the level of soil around the plant was level with the surrounding soil. Soil was firmed around the root ball and a plant identification label attached.

In dry areas and/or those with loose readily drained soils, some operators recommend that the plant be placed in a slight hollow to facilitate the collection and utilisation of water (e.g., Buchanan, 1989). In heavy clay and saline soils, however, mounding is recommended so that the plant roots are not waterlogged or in immediate contact with the saline ground (Buchanan, 1989). At the sites where my field trials were conducted, average rainfall is less than 900 mm per annum, with dry winters and high evaporation; and the soils are also naturally saline (Section 2.1.2). With the variation in rainfall across the year and the high clay content of the soils, there was also concern that, during the wetter months, the plants would become waterlogged, while in winter when rainfall is lower the plants may suffer drought conditions. With this information suggesting two opposing strategies, I decided that the plants would be installed level with the ground. The other alternative would have been to moat the plants with the plant ball itself planted into a mound surrounded by a hollow area which could collect water. I considered that this procedure was not suitable due to the prohibitively large amount of work involved, not only for these trials, but also in the practical sense of providing recommendations for the revegetation of future sites. In addition, the plants chosen for the field trials were all known to grow in the Cumberland Plains area on clay soils, the same general conditions present at the site.

At Site 2, in the top planting area, several of the planting holes had to be partly dug with a trowel and/or crowbar due to the rocky nature of the soil at this part of the site. This resulted in a more spread out hole with relatively uneven sides and some mixing of the pot and field soil.

3.4.2.5 Tree guards

Based on the amount of herbivory that was experienced at Site 1, tree guards were installed around the plants in April 1996. Guards were only put around those plants which appeared to be alive (i.e., health rating better than 5). Those plants which were in poor health when the guards were installed (i.e., health rating of 4), and subsequently died, were placed in the pre-guard death category.

The guards installed were green plastic, with holes to aid airflow (SureGrow^{TM}), held in place with three cane stakes. These guards would have altered the microclimate around the plant in several ways: by increasing the humidity around the plant; by providing a surface for dew to collect which would then run down to the soil in the immediate vicinity of the plant; and through decreasing evapotranspiration due to wind.

As Site 2 was planted after Site 1, and after the herbivory problem had become apparent, guards were installed at the time of planting for this site.

3.4.3 Results

Overall, plant survival at the two sites was quite low, and, as for the germination pilot studies, was quite variable both between areas and between species. The survival for most of the species at Sites 1 and 2 declined rapidly up to 6 months, then again to 12 and 24 months (Figure 3.2). Of particular importance is that for *Daviesia genistifolia* at Site 1; and *Acacia linifolia*, *Kennedia rubicunda* and *Acacia ulicifolia* at Site 2, was that the 2 year survival was 0. With no plants surviving there is no opportunity for future plants for those species. The best survival rate out of the species tested was *Lomandra longifolia* at both Sites 1 and 2.

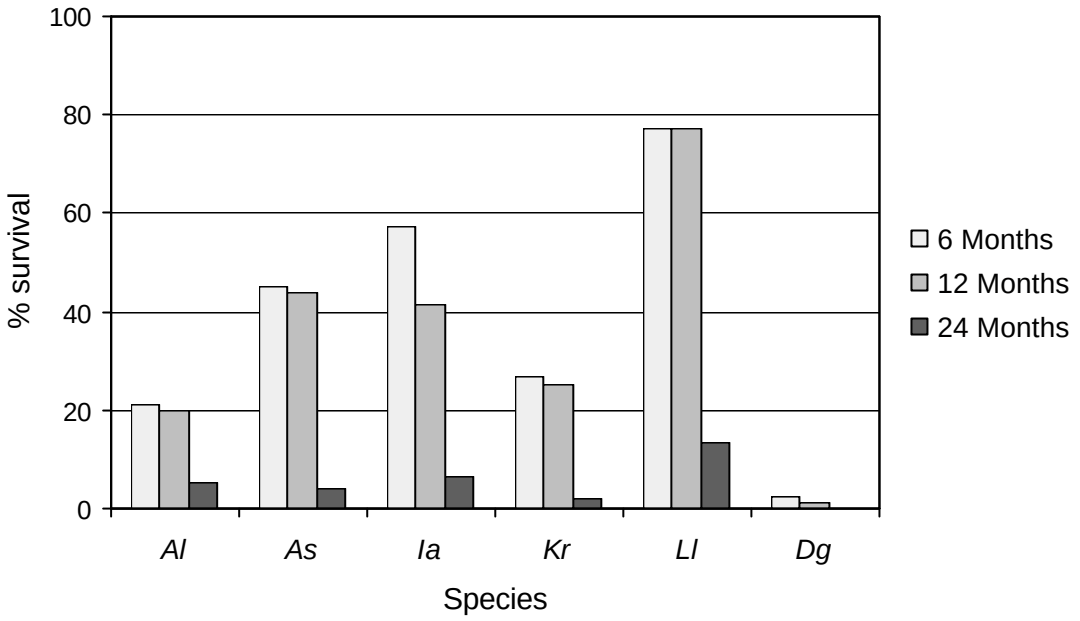


Figure 3.2a Site 1

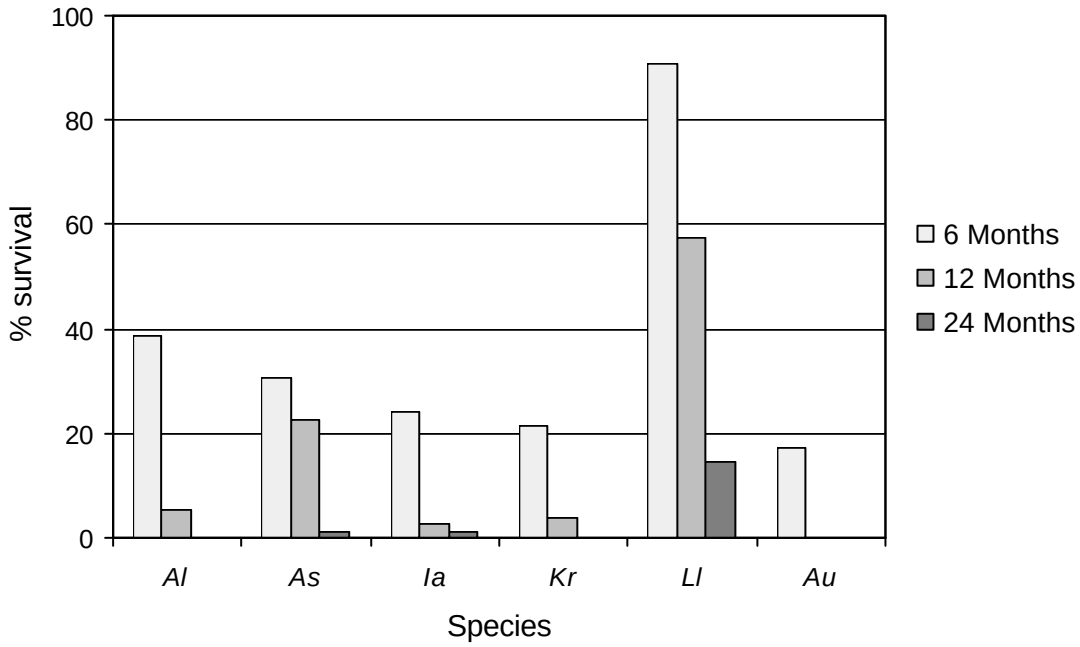


Figure 3.2b Site 2

Al – Acacia. linifolia; As – Atriplex semibaccata; Ia – Indigofera australis; Kr – Kennedia rubicunda; Ll – Lomandra longifolia; Dg – Daviesia genistifolia; Au – Acacia ulicifolia.

Figure 3.2 Plant survival at Sites 1 and 2 for each species after 6, 12 and 24 months

For each of the species, at both Sites 1 and 2, 6 month survival levels were examined and the percentage of plants dying primarily due to herbivory noted (Figure 3.3). Two species at Site 1 were the most highly impacted by herbivory, *A. linifolia* with between 31 and 94% of plants dying through the direct influence of herbivores, and *D. genistifolia* with between 33 and 80%.

Plant survival and deaths attributable to herbivory were then compared across planting areas to see if there was variability across the sites (Figure 3.4). Variability was quite high between planting areas at both sites and was different between the species. At Site 1, for example, planting area 3 had the highest portion of plants surviving for *I. australis* while for *A. linifolia* and *L. longifolia* it was the lowest.

The high impact from grazing animals came from a range of sources. At Site 1, the grazing animals identified were horses, cattle and hares. The horses and cattle were identified by personal observation, scats and hoof marks. The presence of these animals was unexpected, as the site was fenced and the presence of such animals is inconsistent with the use of the site for mining and associated rehabilitation activities. Horses were found to be present at Site 1 during germination Pilot study I due to damage to a boundary fence; this fence had been repaired so these animals should not have been on the site. The hares were identified from their known presence at the site, the small round scats containing plant material found scattered in areas where they had been feeding, and the presence of diggings associated with the scats (Triggs, 1996). At Site 2, in addition to the hares, goats were also present. These animals were identified in observations by site personnel, and at the plot sites through the presence of the small hoof marks and the tapered scats (Triggs, 1996). Again the presence of large grazing animals was unexpected and this site had well-maintained fences. It would appear that at Site 2 the goats were actually fenced onto the site.

Apart from being eaten, many plants were also trampled; this was most prevalent at Site 1. Once tree guards were installed around the plants, little large scale herbivory of the plants was observed. Much fewer deaths attributed to herbivory occurred at Site 2 due to the use of tree guards, 13% as opposed to 30% at Site 1 (comparing the 5 species in common to both sites) due to the tree guards mostly being installed at the site of planting (see Section 3.4.2.5). Some herbivory, however, still occurred due to two factors. Firstly, for planting area 5

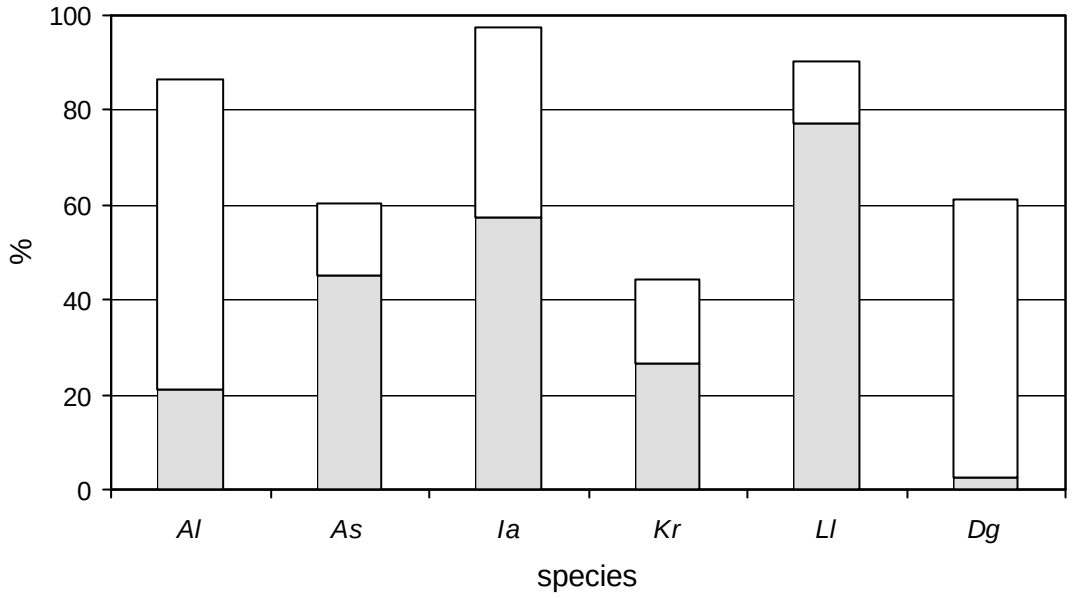


Figure 3.3a Site 1

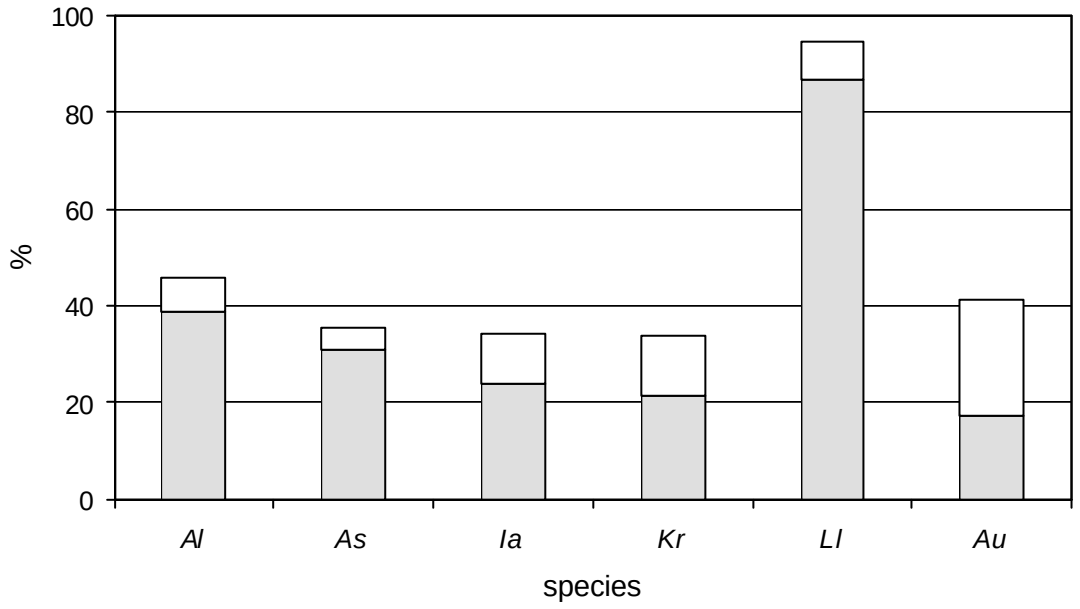


Figure 3.3b Site 2

Al – Acacia linifolia; As – Atriplex semibaccata; Ia – Indigofera australis; Kr – Kennedia rubicunda; Ll – Lomandra longifolia; Dg – Daviesia genistifolia; Au – Acacia ulicifolia.

Figure 3.3 Plants alive (stippled portion of bar) and deaths attributed to herbivory (open portion of bar) at Sites 1 and 2 for each species after 6 months (see Figure 3.4 for variability across the planting areas)

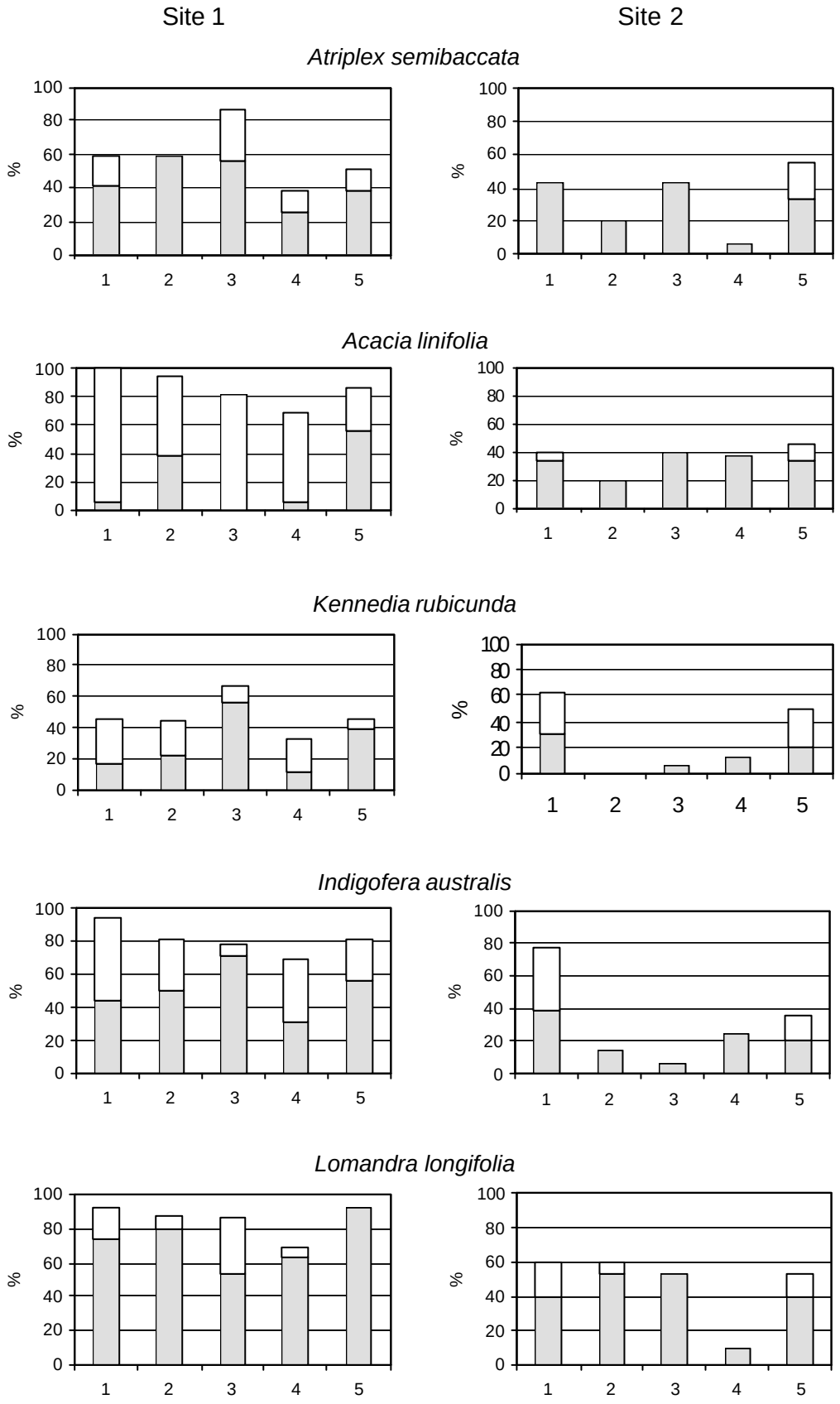


Figure 3.4 Plants alive (stippled portion of bar) and deaths attributed to herbivory (open portion of bar) for each planting area (1-5) and species at Sites 1 and 2 after 6 months

(northeast) the tree guards were installed one to two days after planting. On this occasion many plants suffered a lot of herbivory from both hares/rabbits and goats (18.8% of losses attributed to herbivory at this area compared to an average of 4.8% at the other four planting areas). The other problem was that some of the canes from the plant-guards were removed by vandals. When this occurred, the guards no longer provided the plants protection from herbivores (this accounted for most of the herbivory at planting area 1, see Figure 3.4). Loose guards also damaged plants in windy conditions with the movement of the plastic guard material across the plant.

As expected, overall plant deaths attributed to herbivory were lower at Site 2, 13% as opposed to 30% at Site 1 (comparing the 5 species in common to both sites), with tree guards mostly being installed at the time of planting at this site (see Section 3.4.2.5).

Grazing pressure was generally the most detrimental immediately after planting when the root ball was small and not firmly anchored to the substrate. In this case, some plants were actually pulled out of the ground when grazing occurred, which allowed no opportunity for regrowth. Also, at the time of planting, with the root balls being quite small, there was little tissue from which regrowth might occur.

3.4.4 Discussion

In the planting experiment, there was high variability in the survival and herbivory rates between the species, as had been noted in the germination pilot studies. This confirms the need to use a variety of species in trials and not to draw conclusions based upon one or two species. Ideally, many more species would be used, but, the number of species will always be limited at some point by the space, time and money.

Herbivory by horses and cattle (Site 1) and hares and goats (Site 2) was found to be a major factor in the loss of plants from this experiment. This result was unexpected due to the landfills being located on active mining sites which were fully fenced. Initial site observations had also indicated that the only large herbivores present at these sites were hares (see Sections 2.2.1 and 2.2.2). In the early germination experiment at Site 1, horses were found to be present, but these were removed and the fence repaired.

I observed that the cattle seemed to walk along the rip lines at Site 1, with the result that many of the plants were trampled rather than eaten. Horses were also observed moving directly to planting areas, so it is possible that either the open nature of the planting in the riplines, or the marking of the plants made them easier to find. Ashby (1997) also found herbivory (by deer) to be an important factor in the growth and survival of plants with some species being much more heavily grazed than others. Additionally, Ashby found that herbivory was also greater in the ripped areas and suggested it was because the plants were easier to find.

The soils at Sites 1 and 2 have been identified as being low in nutrients, including phosphorus and nitrogen (see Sections 2.2.1 and 2.2.2). Each plant was individually fertilised using 5 g of N:P:K 17.0:1.6:8.7 at the time of planting. In addition, fertiliser was applied to the soil when the cover crops were sown prior to the planting (see Sections 2.2.1 and 2.2.2). The species selected for use in the trials grow naturally in the low nutrient soils of the area. For these reasons, low soil nutrient levels were not expected to be a factor in the survival of the experimental species.

Several characteristics of the sites result in low soil moisture availability, including climate, low organic content of the soil and soil compaction (see Sections 2.2.1 and 2.2.2). The plants were not watered artificially and so were dependant upon rainfall and the water holding capacity of the soil. It is important to note that some plants of some species did grow, therefore, low rainfall cannot, by itself, be the limiting factor for vegetation survival. Low available soil moisture could, however, be the major limiting factor through low soil water holding capacity and variations in microclimate. Various experiments described in Chapter 4 examine the importance of soil moisture as a limiting factor for germination and survival.

3.5 Implications of germination Pilot studies I and II and planting experiments: Sites 1 and 2

There were a number of consistencies between the germination pilot studies and the planting experiment. Firstly, there was the low overall success, in terms of both germination and survival of the germinants and plants. Secondly, there was a large variation, between sites, between quadrats and planting areas, and between species. Importantly, one of the species

which showed zero germination in the germination studies, *Lomandra longifolia*, had the highest survival rates in the planting experiment. If a species is much more successful, or only successful, when either direct seeded or planted, then this would markedly influence advice given on the revegetation of a site.

In the next chapter, I describe a series of experiments designed to test the importance of granivores, rainfall and soil moisture levels, for germination and survival. Additionally, some of the remaining plants were destructively sampled to provide information on below ground health and growth as a comparison to above ground (Section 4.6).

Chapter 4
Investigation of factors influencing germination and survival

4.1 Introduction

In the previous chapter, I identified climate, soil moisture levels, seed removal and herbivory, as factors that were likely to be contributing to the observed low germination rates, poor seedling survival and poor plant survival. The aim of the series of experiments that comprises this chapter was to test the extent to which these factors do actually affect germination rates and/or seedling survival. Impacts of these factors on germination rates were examined in three ways: (i) glasshouse experiments looking at the impact of climate (Section 4.2); (ii) field experiments adding mulch and water to increase soil moisture in the field (Section 4.3); and (iii) field experiments measuring levels of seed removal from caches at the experimental sites (Section 4.4).

I also attempted an experiment to determine whether the marking of plants in the field with stakes and coloured tape made them more susceptible to herbivory (Section 4.5). Following on from the main planting experiment (Section 3.4), excavation studies were undertaken to examine the root systems of surviving plants. As survival rates were so low, some plants from other experiments and trials were also sampled (Section 4.6).

4.2 Influence of soil moisture on germination: Site 2

4.2.1 Introduction

From the pilot studies (see Sections 3.2 and 3.3), low rainfall, with consequent low soil moisture, was identified as a factor most likely to be contributing to the low germination and seedling survival rates. The aim of the experiment described here was to determine the degree to which climate, particularly moisture aspects, contributed to the poor germination and survival rates recorded in the field, by comparing the germination rates found in the field at Site 2 with germination of a selection of the same species in glasshouse conditions. The glasshouse experiment was conducted using soils collected from adjacent to the experimental quadrats at Site 2 (see Section 3.3).

If low soil moisture levels, rather than other soil factors, were responsible for the low germination rates observed, it is expected that germination rates in the glasshouse would be much higher than those observed in the field. Additionally, if soil moisture levels were the only limiting factor, germination rates in the glasshouse would be expected to be to be the same in soils collected from the field, and those in the control trays (vermiculite:perlite).

4.2.2 Materials and methods

4.2.2.1 Germination in the field

The field part of the experiment was the 10 quadrat study set up at Site 2 in May 1996 (see Section 3.3.2). The 11 species used were: *Acacia linifolia* (batch Al-1), *A. ulicifolia* (batch Au-1), *Atriplex semibaccata* (batch As-1), *Bursaria spinosa* (batch Bs-1), *Daviesia ulicifolia* (batch Du-1), *Dillwynia juniperina* (batch Dj-1), *Hardenbergia violacea* (batch Hv-2), *Indigofera australis* (batch Ia-1), *Kennedia rubicunda* (batch Kr-2), *Lomandra longifolia* (batch Ll-1) and *Melaleuca thymifolia* (batch Mt-1). For nine of the species, 100 seeds were sown per quadrat; for the other two species, due to their small size, a weighed amount of seed was used: *B. spinosa* (0.2 g) and *M. thymifolia* (0.1 g). For seed treatment and base germination rates refer to Table 2.4.

4.2.2.2 Germination in the glasshouse

Soil was collected from adjacent to each of the field quadrats at Site 2, taken into the glasshouse and sown with a selection of the experimental species. A soil sample was also collected from adjacent to each of the quadrats and transported to the laboratory for air-drying and future analysis as required.

The punnets used for germination in the glasshouse were 150 mm x 100 mm and 50 mm deep. Each punnet was washed in soap and water, then a dilute disinfectant solution, and finally rinsed with water. A section of field soil was cut to fit each punnet, using the edge of a spade. The spade was then used to transfer the soil section into the punnet with as little disturbance as possible and with the top surface remaining on top.

Seven sections of material were collected from within a 1 m radius of each of the ten field quadrats at Site 2 (giving a total of 70 punnets). The seven samples from around each quadrat were placed together in a tray and transported back to the glasshouse. In each of the trays, one control punnet with 50:50 vermiculite:perlite, was included (total of ten control punnets).

The soil surface in each punnet was raked, seed was sown and the surface lightly raked again until the majority of the seed was covered, replicating the method used in the field (Section 3.3.2). The trays were watered daily using automated overhead sprinklers.

Logistical constraints limited the amount of soil that could be collected and the number of trays that could be managed in the glasshouse. This also limited the number of species which could be tested. For the glasshouse experiment, 6 out of the 11 species from the field experiment were used. The final list of six species used in the experiment and why they were selected is provided in Table 4.1. *Lomandra longifolia* was not selected due to its slow germination rate and *Melaleuca thymifolia* was not used because the seed is too small to be counted reliably (see Table 2.4). Seeds were treated as described in Table 2.4.

Table 4.1 Species used in the glasshouse experiment, selection criteria, and the number of seed used per punnet

Species	Selection criteria	Number of seeds per punnet	Number of punnets the species was sown in per tray
Acacia linifolia	Reasonably fast & high germination rate	10	All 8
Atriplex semibaccata	Fast germination rate, high salinity tolerance, poor field germination	10	All 8
Bursaria spinosa	Seed collected from the area in similar soils	15	All 8
Daviesia ulicifolia	Seed collected from Site 1 in similar soils	5	All 8
Hardenbergia violacea	Fast germination rate, occurs naturally at Site 2	10	4 field soil punnets plus control punnet
Kennedia rubicunda	Fast & high germination rate, used in all other studies	10	3 field soil punnets plus control punnet

Seeds of *Hardenbergia violacea* and *Kennedia rubicunda* were separated in the punnets containing field soil as both of these species had exhibited good germination rates and have large seedlings. The concern was that these two species, if good germination occurred in the field soil, would quickly cover the soil, both in leaves and with the root system, which may then limit the germination of other species.

No germination occurred for *B. spinosa* in the field, glasshouse or control. This species is therefore not discussed further in relation to this experiment.

4.2.3 Results

Germination in the field was low; less than 5%, for all ten species tested (see Section 3.3.3). For the five species tested in the glasshouse, the average germination rates in the field were: *Acacia linifolia* 3.7%; *Atriplex semibaccata* 4.1%; *Daviesia ulicifolia* 0.4%; *Hardenbergia violacea* 2.7%; and *Kennedia rubicunda* 2.3%. Total germination per quadrat for these five species ranged from 0.4-7.4%

Germination for all five species tested was highest in the control (vermiculite:perlite), intermediate in the glasshouse experiment, and lowest in the field (see Figure 4.2.1). This figure clearly shows the large difference in germination between the field and the glasshouse, both in the field soil and the vermiculite:perlite control, with germination rates in the glasshouse trials more than 10 times greater than in the field. The hypothesis that germination rates in the glasshouse would be significantly different from rates in the field was supported for the five species tested (one-way ANOVA, randomised block design, $F_{x,y} = 243$, $P < 0.0001$).

The second hypothesis, that germination in the glasshouse would be significantly different for the vermiculite:perlite and the field-collected was accepted for four species, with levels of significance of 0.01 or less (one-way ANOVA randomised block design): *A. semibaccata* ($F_{x,y} = 11.33$, $P = 0.008$), *D. ulicifolia* ($F_{x,y}=23.20$, $P = 0.001$), *H. violacea* ($F_{x,y} = 11.33$, $P = 0.008$), *K. rubicunda* ($F_{x,y} = 9.97$, $P = 0.012$)(see Figure 4.2.1).

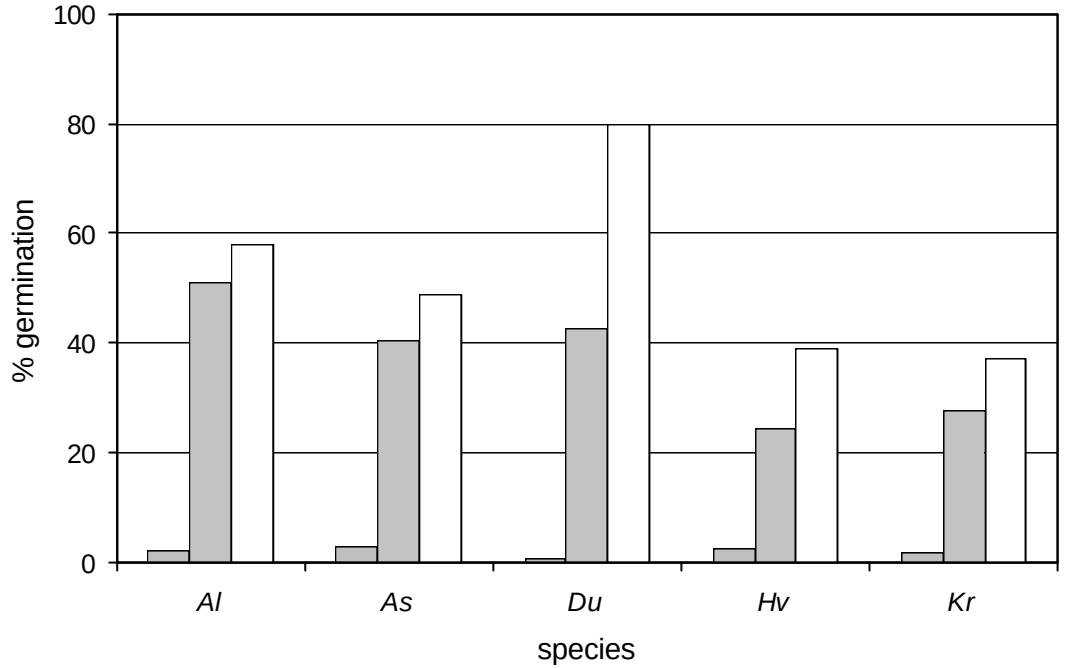


Figure 4.2.1 Overall percent germination by species, for the field (stippled bars; Site 2), glasshouse (hatched bars) and control (open bars; vermiculite:perlite). (*Al = Acacia linifolia*; *As = Atriplex semibaccata*; *Du = Daviesia ulicifolia*; *Hv = Hardenbergia violacea* and *Kr = Kennedia rubicunda*)

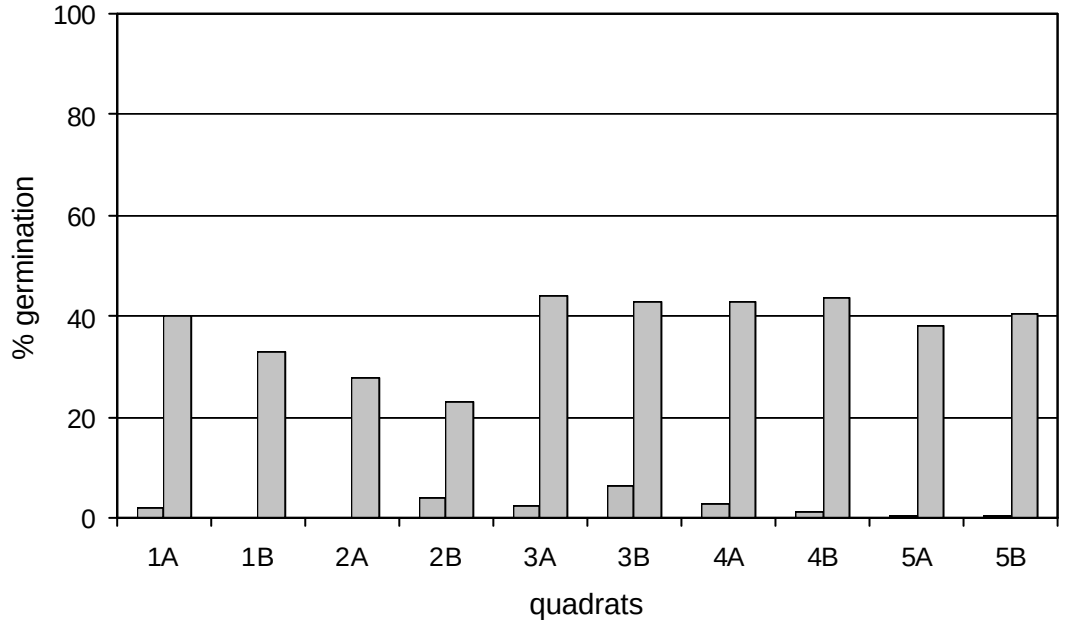


Figure 4.2.2 Overall percent germination in the field (stippled bars; Site 2) and glasshouse (hatched bars) for each of the quadrats for the five species tested (see Figure 4.2.1)

No significant difference was found for *A. linifolia* ($F_{x,y} = 0.80$, $P = 0.40$). In all cases the germination rates in the vermiculite:perlite control were higher than those for the field soil.

There was some variability in the field and glasshouse germination between the quadrats (see Figure 4.2.2). The variation between the quadrat soil samples in the glasshouse indicates that either soil factors or differences in light and moisture affected the germination. There does not appear to be any correlation between the rate of germination in the field and in the glasshouse for individual quadrats (see Figure 4.2.2).

4.2.4 Discussion

The significant difference between the field and glasshouse germination for each of the species means that, whatever the limiting factors are, they are either not present in the glasshouse or they are present to a lesser degree than in the field. Differences include daily watering with subsequent increase in soil moisture content; screening from wind, sun and reduced diurnal temperature fluctuations; absence of granivores and herbivores; changes to soil characteristics such as salinity as a result of the watering and reduced evaporation; and the absence of landfill gas.

During the experiment, the temperature in the glasshouse ranged from 14-28°C, whilst the field temperatures ranged from 1-24°C with warmer temperatures experienced at the later part of the study (Station 067019; Bureau of Meteorology, 2005). If temperature was the limiting factor in the field, it would be expected that there would be no germination initially, with increasing germination as the experiment progressed and temperatures increased; this was not the case.

The germination in the vermiculite:perlite was significantly higher for four of the five species, than the glasshouse experiment using the field soils. These results show that there is a difference to the germination between the field soil and the vermiculite:perlite control, however, these differences are not important for all species. Therefore, one or more soil factors, apart from soil moisture, limited germination in the field soils for some species. Factors which may explain these differences in germination include high salinity, and low pH (see Sections 1.5.5.3, 1.5.5.4 and 2.2.2).

During the field experiment, several chewed seeds were observed. In the previous studies (see Sections 3.2.4 and 3.3.3) some seeds were hollowed and others moved. In Section 4.4, two field studies are described which looked at the potential loss of seeds from the site and how important seed removal may be in the low germination rates observed.

Low soil moisture would appear to have been a highly limiting factor to germination in the field at this site. A field germination experiment using watering and mulching to boost soil moisture levels is described in Section 4.3.

4.3 Soil moisture as a limiting factor for germination and seedling survival: Sites 2 and 3

4.3.1 Introduction

Soil moisture content was found to be a limiting factor in the pilot studies and was inferred from the climatic information (see Sections 2.1.1 and 4.2). The species studied were chosen based upon knowledge of their ability to grow in dry and/or drought prone areas (see Section 2.3.1), so the next step was to investigate the effect of varying soil moisture in the field. There are three broad ways in which soil moisture can be increased: changing the soil characteristics such as increasing the clay (in clay poor soils) or organic content; adding mulch or some other insulation layer on top of the soil; or through the addition of water.

As the clay content of the site soils was already high, I designed an experiment to test the impacts on germination of watering and of mulching of direct-seeded plots at Sites 2 and 3. The mulch would help to conserve water and is easy to replicate in a management situation. The watering would be the equivalent to irrigation, and as such, would also be easy to replicate. This study was conducted over one year, with the focus being on the water requirement for germination and early plant survival.

The hypotheses tested were:

i. The relative order of seedling survival results, over one year, would be: mulched and watered > mulched or watered > no treatment; and

ii. The relative order of total germination results, over one year, would be: mulched and watered > mulched or watered > no treatment.

4.3.2 Materials and methods

The mulching and watering experiment was installed as a randomised block design at Sites 2 and 3. Each of ten replicate plots, at each site, contained four quadrats, allocated randomly to each of (i) no treatment, (ii) watered, (iii) mulched, and (iv) watered and mulched. At Site 2, two plots were randomly assigned to each of the five topographic areas of the site (top, northeast, northwest, southwest and southeast). At Site 3, five plots were randomly assigned to each of the two landfill areas available.

The plots were 5.5 m long and 1 m wide, oriented approximately along the contour, to limit movement of seed and/or mulch from one treatment to another through runoff. Each of the quadrats was 1 m by 1 m with a distance of 0.5 m between (Figure 4.3.1). The space between the quadrats provided sufficient room to separate the treatments and to allow movement between the quadrats for monitoring. The size of the quadrat ensured ready access to all parts of the area for accurate monitoring, plus, kept the overall size small enough so that it could be installed in areas with similar characteristics, such as soil type. The corners of each quadrat were marked with ribbon.

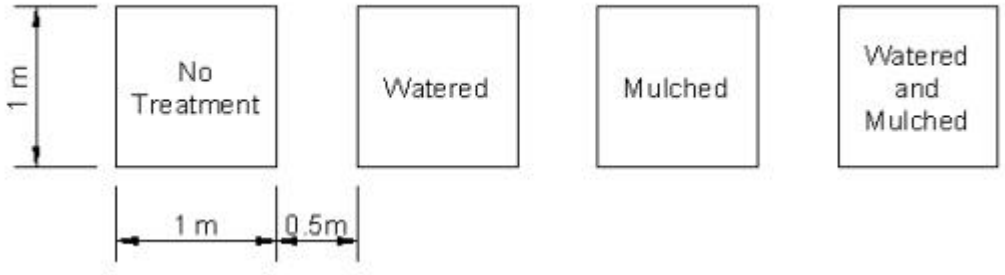


Figure 4.3.1 Outline of mulching and watering experimental plots, example of Plot 1, Site 3

Twelve species were used in this experiment. For six of the species: *Acacia linifolia* (batch Al-3), *Atriplex semibaccata* (batch As-1), *Hardenbergia violacea* (batch Hv-3), *Indigofera australis* (batch Ia-2), *Kennedia rubicunda* (batch Kr-3) and *Lomandra longifolia* (batch Ll-3) 200 seeds were used for each quadrat. For two of the species insufficient seed was available for 200 seeds per quadrat, so less was used: D*aviesia genistifolia* (batch Dg-2) 150 seeds and *Daviesia ulicifolia* (batch Du-1) 98 seeds. For species with smaller seeds, a specific weight of seed was used in each quadrat: *Bursaria spinosa* (batch Bs-3) 0.30 g, *Calotis cuneifolia* (batch Cc-1) 0.10 g, *Melaleuca thymifolia* (batch Mt-2) 0.10 g and *Ozothamnus diosmifolius* (batch Od-2) 0.30 g. *Acacia ulicifolia* was not used in this experiment, as seed was difficult to obtain. Seeds either received no treatment or boiling water treatment depending upon the species (see Table 2.4).

The quadrats were first raked to remove any existing mulch, including that formed from dead grasses. All existing vegetation in the plots was clipped to a height of 50 mm, or in the case of couch or other creeping grasses, to the base. The resulting mulch and clippings were placed down-slope from the quadrats to prevent material from being washed back onto the quadrat through runoff. Seven grooves were hoed into each of the quadrats along the contour using a mattock. The seeds were then spread into each of the grooves and the soil lightly raked to cover the seed.

The mulch for the trial was a thin layer of straw giving 100% ground cover at the time of laying. The straw has the advantages of being cheap, easy to install, contains a minimum of potential weed seed, and can be spread though a hydromulch technique and, is therefore suitable for use over large areas and on steep slopes. Another commonly used, and readily available, mulch is wood chip. Problems associated with the use of this type of mulch include chemical leaching, uptake of nitrogen and physical restriction to emerging seedlings. Another option would be to use a light leaf mulch.

For the watering treatment, the equivalent of 1 mm of rainfall was applied weekly if there had been no rain in the previous week. Tap water was used to ensure the composition of the water being applied was consistent across the sites and plots. Rainfall at each of the sites was monitored a minimum of weekly during the study.

The quadrats were generally monitored every three weeks for the first 6 months then monthly for the second 6 months (Sheet B3, Appendix B). All plots were inspected on a weekly basis for problems, such as vandalism, presence of herbivores, and to apply the relevant watering treatments.

Each of the seedlings were individually marked with a painted wooden toothpick so seedlings germinating between monitoring periods, could be identified as new germinations. This allowed the differentiation between germination numbers and seedling survival rates.

4.3.3 Results

As for the earlier germination trials (see Chapter 3), variability between the species, plots and sites was high. Germination was generally low, and for some species (Section 4.3.3.1) and quadrats, zero. Other quadrats exhibited good germination rates. I present the seedling survival and total number of seedlings for each treatment after 3, 6 and 12 months for Site 2 (Section 4.3.3.2) and Site 3 (Section 4.3.3.3).

4.3.3.1 Species which failed to germinate

After twelve months, 4 of the 12 species showed no germination at either site: *Bursaria spinosa*, *Lomandra longifolia*, *Melaleuca thymifolia* and *Ozothamnus diosmifolius*. The batches of *B. spinosa* and *O. diosmifolius* used, also exhibited no germination in the controls (see Table 2.4), and were subsequently removed from further analyses. These species had shown no germination in previous trials, thus the treatments used made no difference to germination. This is an important point in the successful revegetation of a site where a diverse community of plants is desired, and certainly, if the aim is to reproduce the original community, then a range of techniques may be required.

4.3.3.2 Germination and seedling survival for each treatment: Site 2

Germination was slow to start, generally taking well over a month, and continued over the 12 months of the study (Figure 4.3.2). Numbers of seedlings alive was greatest at around 3

months, for all four treatments, then gradually, and in some cases rapidly, declined over the next 9 months.

The range in germination after 6 months was from 0 to 43 seedlings per quadrat with no treatment. This was very similar to the results for Pilot study II at Site 2 with 2-37 seedlings per quadrat (see Section 3.3.3). This result is very interesting, as in the second study the number of counted seed per quadrat, in species that have shown germination during the trials, was 1248 plus 0.10 g of *Calotis cuneifolia*, while in the first study it was 800. Therefore, the germination success of the second study was less than the first after 6 months.

The general trend for both the seedlings survival and total germination over 3, 6 and 12 months, was that the mulched and watered treatment had the highest germination, then the mulched, then the watered and finally the no treatment (Figure 4.3.2). This supports the original hypothesis. The biggest difference was between the mulched treatments (both just Mulched and Mulched plus Watered) versus the un-mulched treatments (Watered and No treatment).

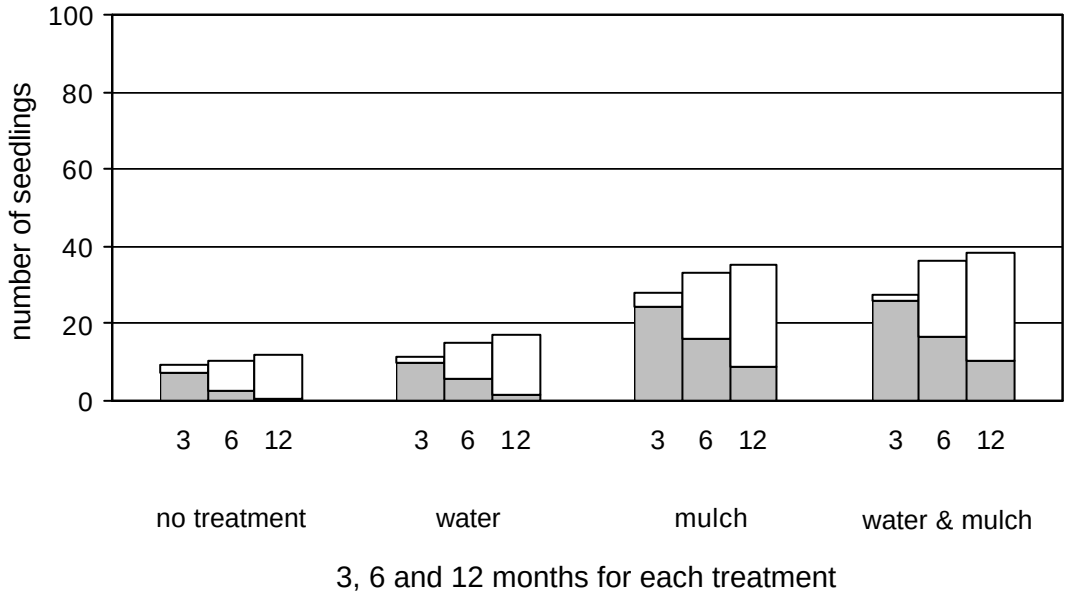


Figure 4.3.2 Site 2, cumulative numbers of seedlings appearing (total bar) and numbers of these alive (open portion of each bar) at 3, 6 and 12 months. Data are averaged across 10 quadrats. For variability between quadrats see Figure 4.3.3

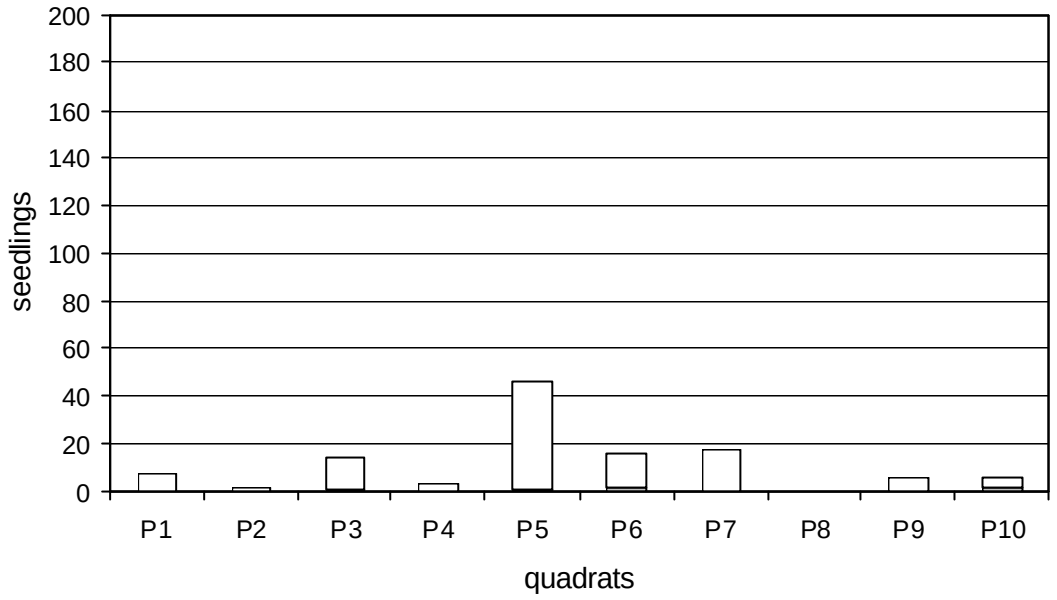


Figure 4.3.3a Site 2—no treatment

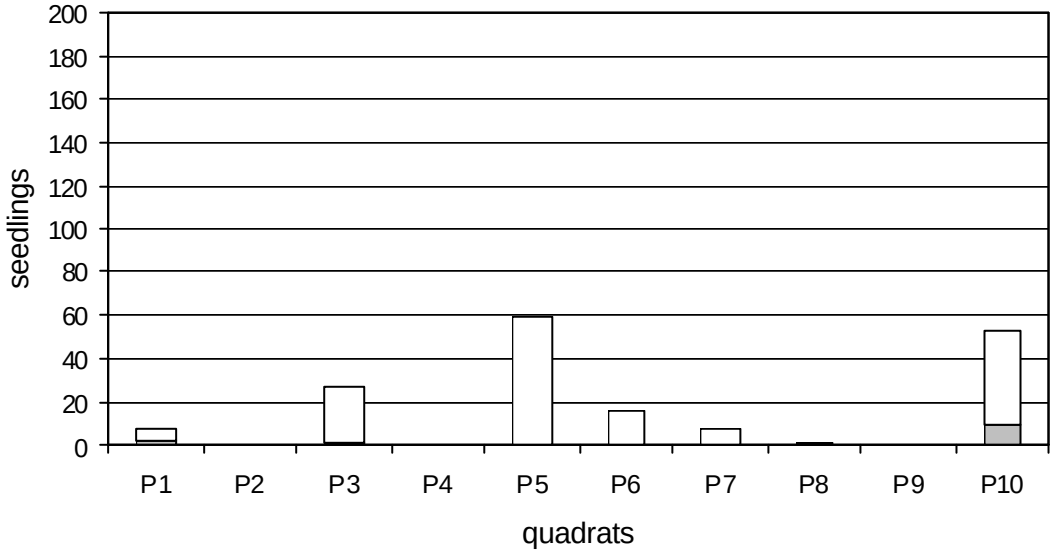


Figure 4.3.3b Site 2—water

Figure 4.3.3 Site 2, cumulative numbers of seedlings appearing (total bar) and numbers of these alive (open portion of each bar) after 12 months for each plot and treatment

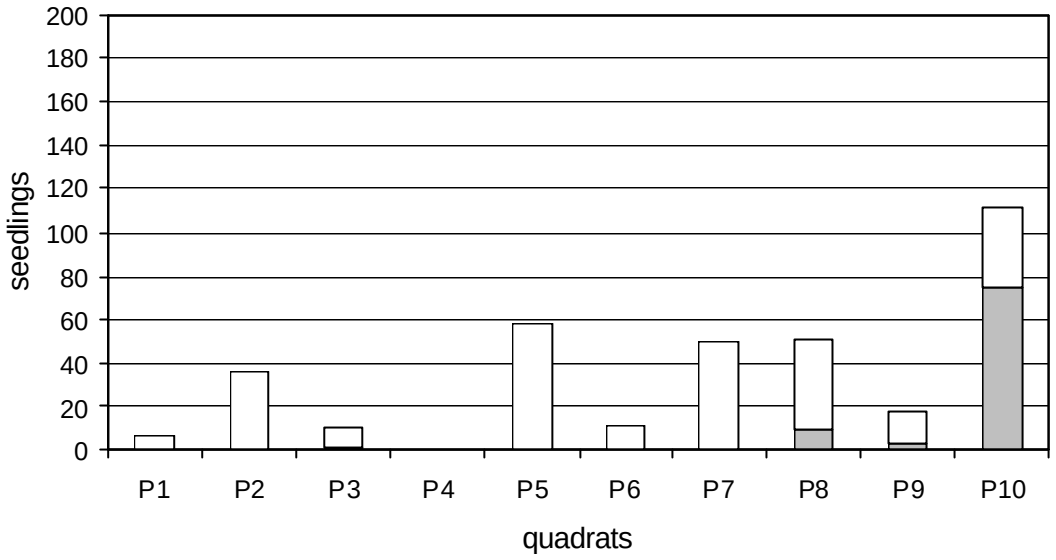


Figure 4.3.3c Site 2—mulch

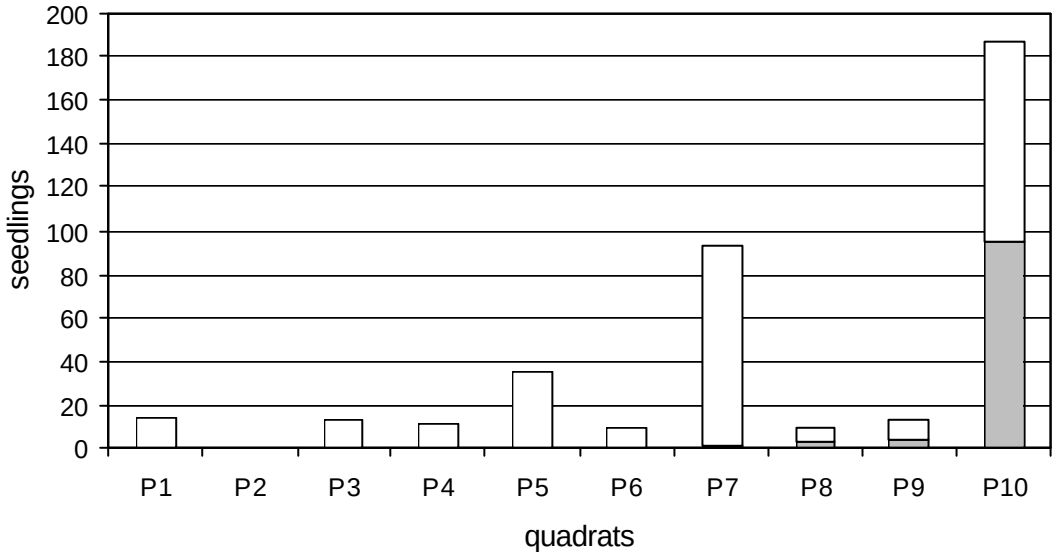


Figure 4.3.3d Site 2—water and mulch

Seedling survival and total germination were very variable across the plots for each of the treatments (see Figure 4.3.3). At three months seedling survival ranged from 0 at 7 of the quadrats (these were across all treatments), to 121 for the Watered and Mulched treatment at Plot 10. After 12 months seedling survival was 0 at 25 of the quadrats, across all treatments; the highest number of surviving seedlings was again for the Watered and Mulched treatment at Plot 10 with 95 survivors.

There were two problems with the statistical analysis of the Site 2 data. Firstly, overall germination rates were low and seedling survival much lower, this resulted in a lot of zeros in the data set. Secondly, there was a possible contamination of the block at Plot 10. Plot 10 was set out with the Watered and Mulched treatment on the left, then Mulched, Watered and finally No treatment (see Figure 4.3.4). Germination in this area of the site, including of the grasses sown as part of the general site revegetation works (see Section 2.2.3) was much higher than most other areas of the site. Plot 10 appeared to be located at the edge of this area such that the Mulched and Watered treatment was actually in the high germination area, whilst the No treatment quadrat was outside. The overall germination and seedling survival for the Mulched & Watered and just Mulched treatments were certainly much higher than those found at the other plots (see Table 4.2). As such, part of the Plot was effected, but, not all: making the block invalid for statistical analysis and comparison of the treatments. Therefore, Plot 10 was removed from the statistical analysis. It should be noted that what happened in this Plot, while unfortunate for the analysis of my dataset, was a very important result. If the factor/s causing the high germination in this area could be determined, and replicated, then a very successful revegetation of this site could be achieved. Apart from the higher germination, and less surface erosion, there were no obvious visual differences between this area and the areas adjacent which showed much lower germination. The appearance of the soils, the slope and aspect were all the same. It is possible that these areas were watered as part of the emptying of erosion control ponds at the bottom of the landfill batter. The areas were the experiments were located were supposed to be avoided. However, it is difficult to ensure that mistakes do not occur when a site is active.

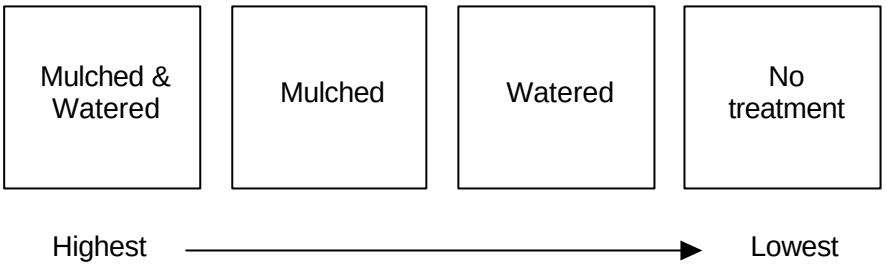


Figure 4.3.4 Site 2, outline of Plot 10. Germination was highest in the left hand quadrat (as shown) and declined from left to right.

A two-way ANOVA (randomised block design) was applied to the total germination for Plots 1-9. No significant difference was found between the treatments ($F_{x,y} = 1.52$, $P = 0.23$). This result is not surprising from the low germination rates found at the site. For Site 2, the hypothesis that the Watered and Mulched treatment would have the highest germination, the Water or Mulched treatments would be intermediate, and No treatment would be the lowest, was not supported. There was however, a general trend for the mulched treatments (Mulch and Water & Mulch) to have both higher germination and seedling survival than the treatments without mulch (No treatment and Water). This difference appears to be quite clear when all Plots are included (Figure 4.3.2 and Table 4.2), but, when just Plots 1-9 are considered the difference is quite small (Table 4.2).

Table 4.2 Site 2, the effect of Plot 10 on the overall results of seedling survival after 12 months for each of the treatments. The 'highest' column was the most number of seedlings surviving in a single quadrat for the treatment.

	No treatment		Water		Mulch		Water & Mulch	
	Highest	Ave	Highest	Ave	Highest	Ave	Highest	Ave
Plots 1-10	2	0.6	10	1.3	74	8.7	95	10.3
Plots 1-9	2	0.4	2	0.3	9	1.4	4	0.9

Germination occurred in six species with most showing very low overall germination (Table 4.3). With such low germination rates statistical analysis of whether the treatments had a

significant affect was not possible. All species with an average of 5 or more germinants over the 12 months for one or more treatments were plotted and two-way ANOVA (randomised block design). For this site the only species that met this criterion was *H. violacea* (see Table 4.3 and Figure 4.3.5). No significant difference was found using an ANOVA ($F_{x,y} = 1.75$, $P = 0.18$). There was, however, the same trend as observed in the species overall, that the treatments with mulch had higher germination than the treatments without mulch (Figure 4.3.5).

Table 4.3 Site 2, 12 month survival and total seedlings for each of the species and treatment, averaged over Plots 1-9

	No treatment		Water		Mulch		Water & Mulch	
Species	Survival	Total	Survival	Total	Survival	Total	Survival	Total
A. linifolia	0.0	1.2	0.0	1.9	0.2	4.3	0.0	3.7
A. semibaccata	0.1	0.2	0.1	0.2	0.0	0.8	0.1	0.2
C. cuneifolia	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0
D. ulicifolia	0.1	0.2	0.0	0.4	0.0	0.3	0.2	0.6
I. australis	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
H. violacea	0.2	7.2	0.2	7.3	1.3	16.0	0.6	13.6
K. rubicunda	0.0	2.7	0.0	2.6	0.0	4.3	0.0	3.9

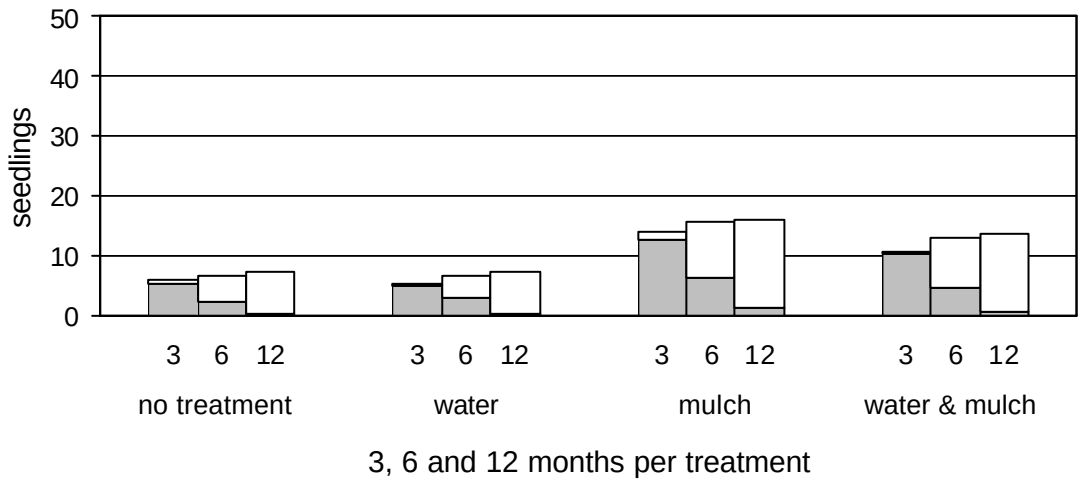


Figure 4.3.5 Site 2, cumulative numbers of seedlings appearing (total bar) and numbers of these alive (open portion of bar) after 3, 6 and 12 months for *Hardenbergia violacea*. Data are averaged across Plots 1-9.

4.3.3.3 Germination and seedling survival for each treatment: Site 3

Germination was a little quicker to start than at Site 2, generally taking 3 weeks, and continued over the 12 months of the trial. Numbers of seedlings alive was again generally highest at around 3 months and declined over the next 9 months (Figure 4.3.6).

Germination occurred in eight species: *Acacia linifolia, Atriplex semibaccata, Calotis cuneifolia, Daviesia genistifolia, D. ulicifolia, Hardenbergia violacea, Indigofera australis* and *Kennedia rubicunda* (Table 4.4). Those species with an average of 5 or more seedlings over 12 months for one or more treatments were plotted and analysed using two-way ANOVA (randomised block design). For Site 3 four species met this criterion: *A. linifolia, D. ulicifolia, H. violacea* and *K. rubicunda* (see Figure 4.3.8 and Table 4.4). For two of the species there was a significant difference between the treatments for total germination, *H. violacea* and *K. rubicunda*. For *K. rubicunda* there was also a significant difference in the 12 month seedling survival (Table 4.5). For the two species where there was no significant difference, the graphs (Figure 4.3.8) certainly reflect this with no observable difference between any of the treatments.

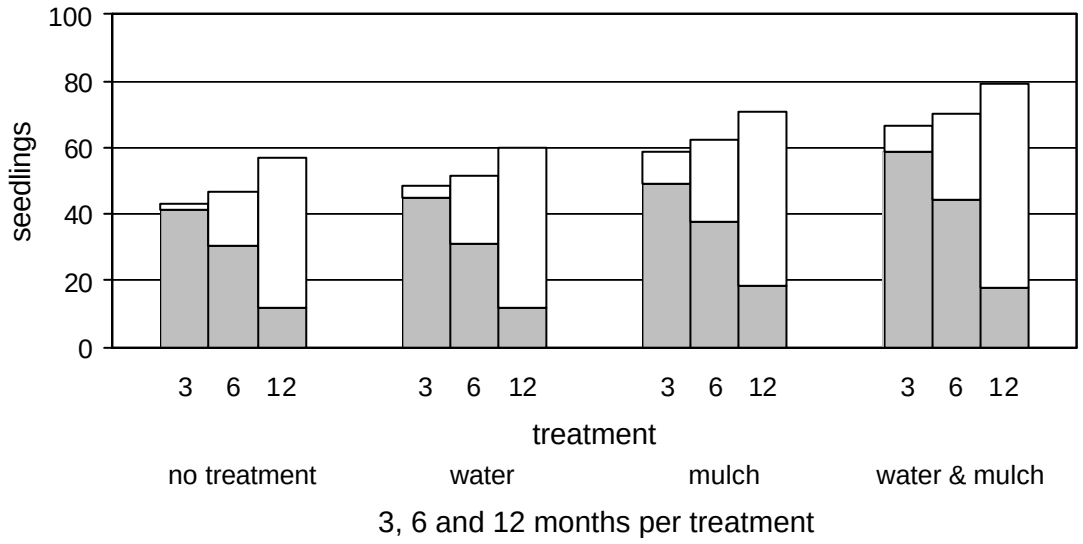


Figure 4.3.6 Site 3, cumulative numbers of seedlings appearing (total bar) and numbers of these alive (open portion of bar) after 3, 6 and 12 months for all species. Data are averaged across 9 quadrats, with data for Plot 7 not included.

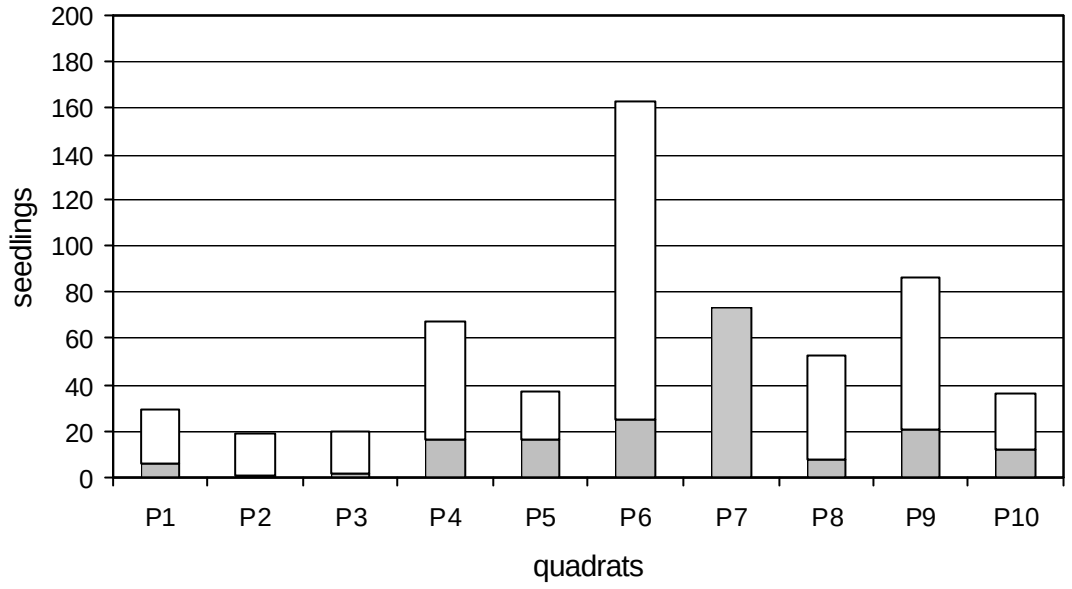


Figure 4.3.7a Site 3—no treatment

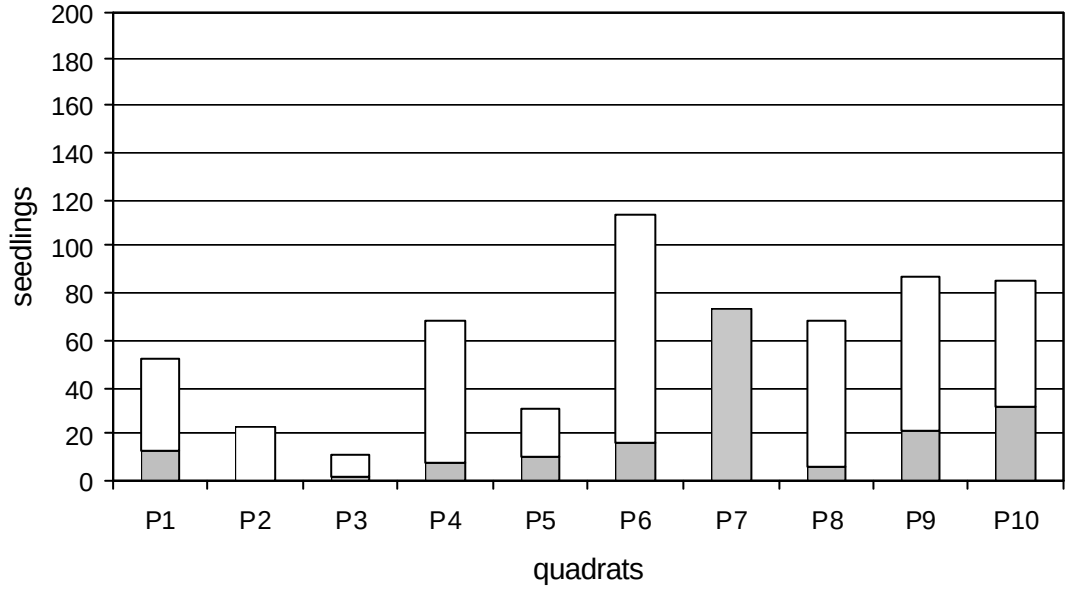


Figure 4.3.7b Site 3—water

Figure 4.3.7 Site 3, cumulative numbers of seedlings appearing (total bar) and numbers of these alive (open portion of each bar) after 12 months for each plot and treatment. Plot 7 values are for 8 months, before the plot was destroyed, no survivors.

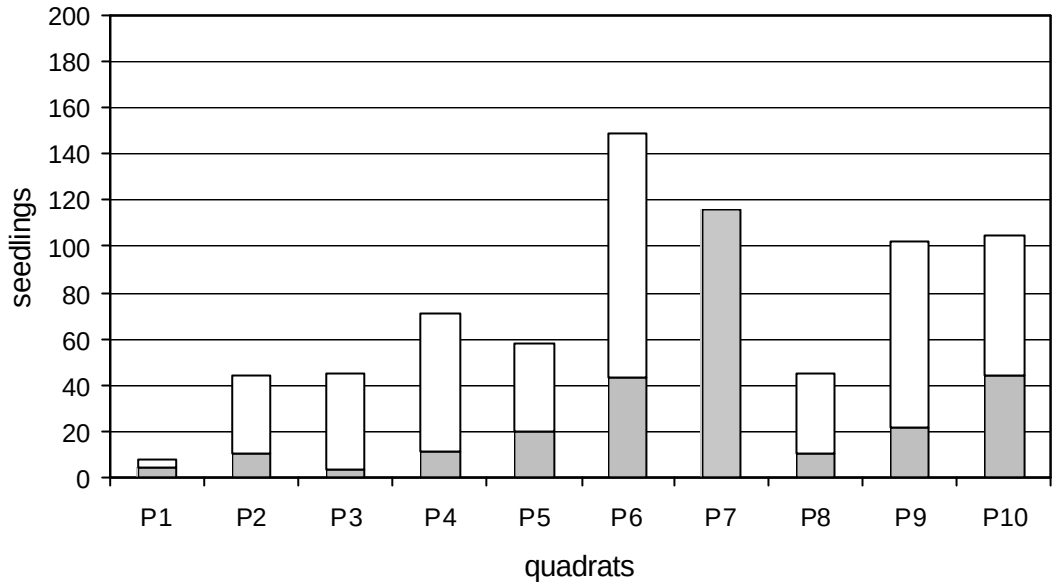


Figure 4.3.7c Site 3—mulch

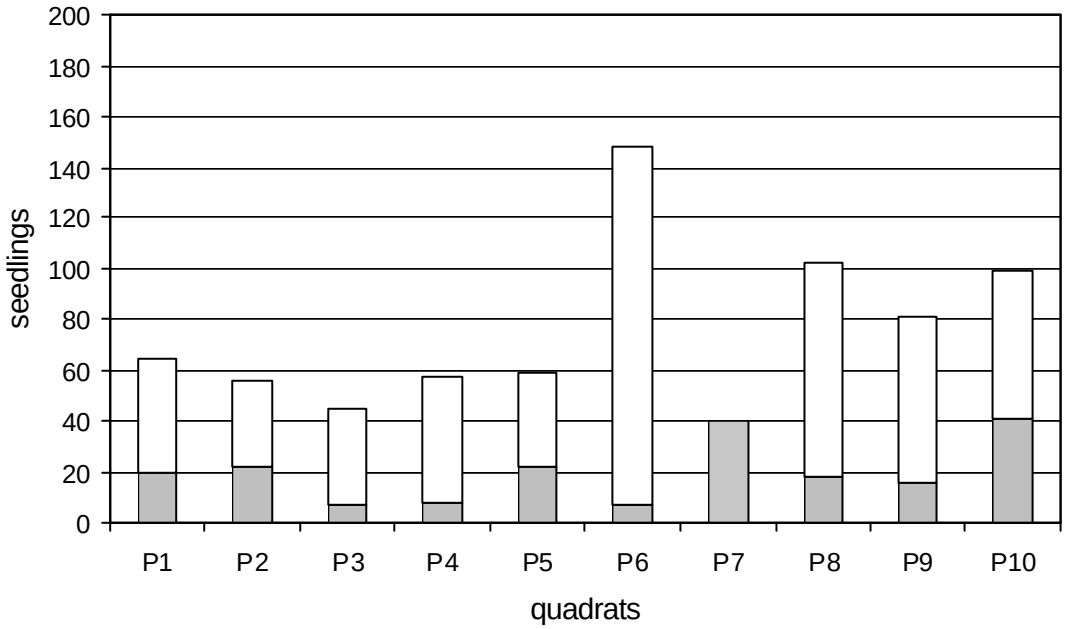


Figure 4.3.7d Site 3—water and mulch

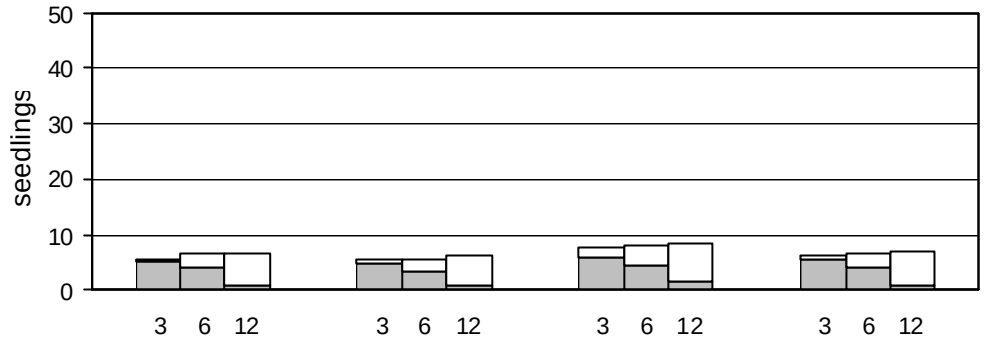


Figure 4.3.8.a Site 3—*Acacia linifolia*

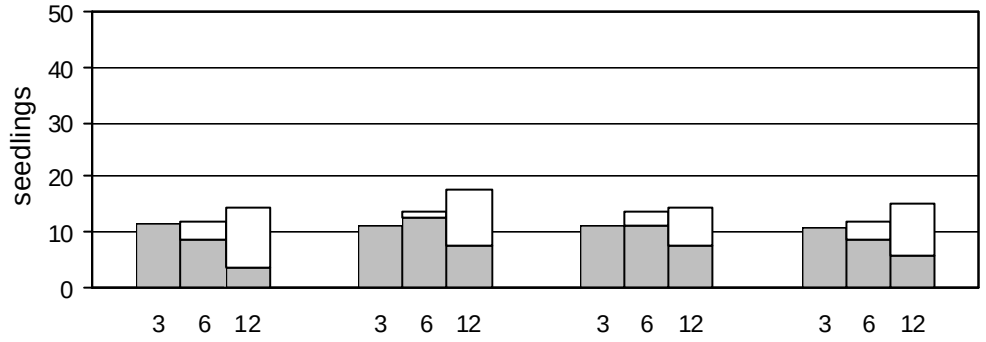


Figure 4.3.8.b Site 3—*Daviesia ulicifolia*, 98 sown per quadrat, values for this graph calculated as a proportion out of 200 to allow comparison with the other species

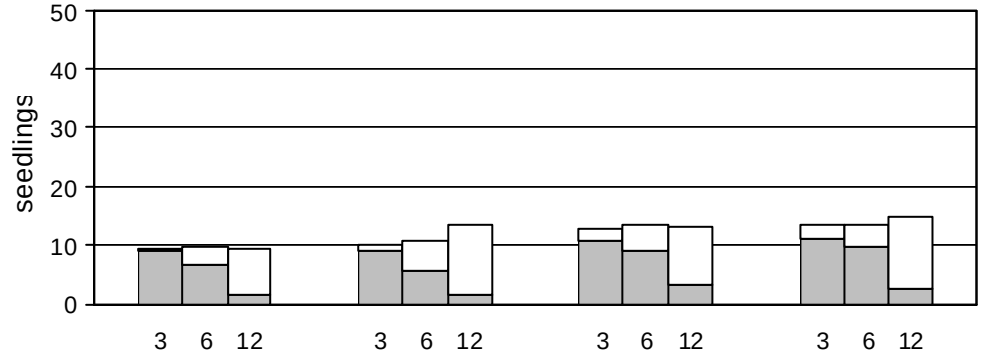
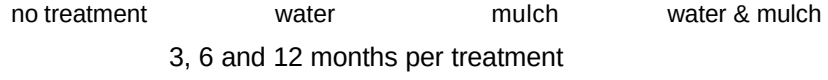


Figure 4.3.8.c Site 3—*Hardenbergia violacea*



3, 6 and 12 months per treatment

Figure 4.3.8 Site 3, cumulative numbers of seedlings appearing (total bar) and numbers of these alive (open portion of bar) after 3, 6 and 12 months for each species. Data are averaged across 9 quadrats, with data for Plot 7 not included.

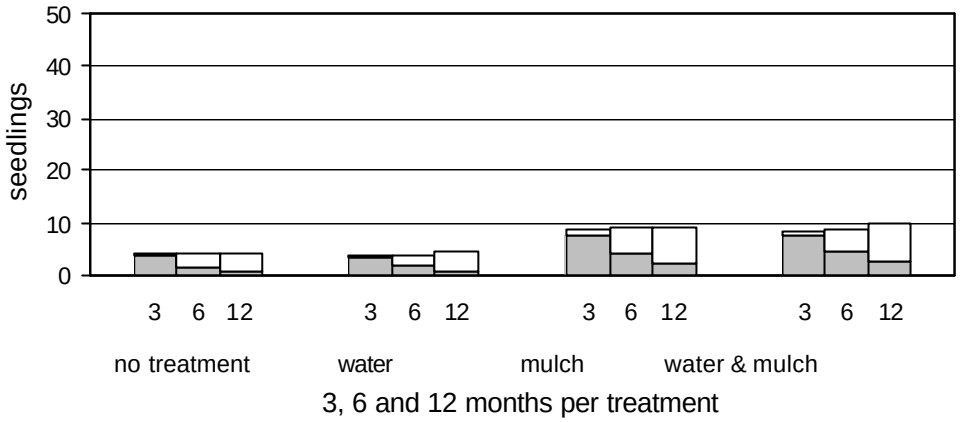


Figure 4.3.8.d Site 3—*Kennedia rubicunda*

Table 4.4 Site 3, 12 month survival and total seedlings for each of the species which had some germination.

	No treatment		Water		Mulch		Water & Mulch	
Species	Survival	Total	Survival	Total	Survival	Total	Survival	Total
Acacia linifolia	1.8	13.2	2.0	12.4	2.3	16.9	2.2	14.0
Atriplex semibaccata	2.9	4.6	1.2	3.2	0.8	1.2	0.8	1.4
Calotis cuneifolia	1.7	3.3	1.1	2.4	2.1	3.8	1.7	2.8
Daviesia genistifolia	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0
Daviesia ulicifolia	1.8	7.0	3.7	8.7	3.7	7.0	4.1	7.4
Hardenbergia violacea	2.3	18.7	2.9	22.0	6.6	25.9	5.0	29.6
Indigofera australis	0.1	1.2	0.2	1.4	0.3	2.8	0.3	3.6
Kennedia rubicunda	1.2	8.2	1.1	9.1	4.0	18.7	4.9	19.9

Seedling survival across the plots at Site 3, for each of the treatments, was again very variable (Figure 4.3.7). At three months, seedling survival ranged from 3 for the no treatment quadrat at Plot 2, to 141 for the no treatment quadrat at Plot 6. This result illustrates the observed variability across both the plots and treatments; as, the 'No treatment' quadrats had the lowest germination overall, the lowest seedling survival rate for a single quadrat, and the highest seedling survival rate for a single quadrat.

For the remaining four species, seedling survival and total seedlings were calculated for 12 months and general trends observed (see Table 4.4). *C. cuneifolia* did not appear to be affected by any of the treatments and the rate of germination for *D. genistifolia* was so low that no comments on trend can be made. *I. australis* followed the overall trend with higher seedling survival and total germination in the Mulched treatments. *A. semibaccata* on the other hand, went against the general trend – the quadrats with the mulch treatment had fewer total seedlings and lower seedling survival. This suggests that reporting combined results for all the species, does not give a good representation of the results for individual species and how they are responding to the treatments. From the individual results for each species (Table 4.4), most of the difference found in the overall germination is attributable to a single species: *K. rubicunda*.

Table 4.5 Site 3, results for 12 month survival and total germination for each species with 5 or more germinants in at least 1 treatment and over all species, using two-way ANOVAs (randomised block design). Species with significant P values (P 0.05 or less) are in bold.

	Survival		Total germination	
Species	$F_{x,y}$	P value	$F_{x,y}$	P value
Acacia linifolia	0.197	0.898	0.96	0.43
Daviesia ulicifolia	2.1715	0.1176	0.34	0.80
Hardenbergia violacea	1.8868	0.1588	**3.64**	**0.027**
Kennedia rubicunda	**8.6336**	**0.0005**	**22.49**	**<0.0001**
Over all species	1.7208	0.1894	**4.41**	**0.01**

The germination and seedling survival rates at Site 3 were much higher overall than at Site 2 (see Figures 4.3.2, 4.3.6). The notable exception to this was for the Mulched and Watered treatment at Plot 10 at Site 2, which with 121 seedlings, was the second highest germination rate of all the quadrats.

4.3.4 Discussion

For many species, the watering and mulching treatments used made no significant difference to either total germination or seedling survival. For other species, such as *Kennedia rubicunda* at Site 3, the Mulching treatments resulted in a significant increase in both seedling survival and total seedlings.

There was very high variation between the two sites, the species and the plot areas. In some cases, such as Site 2, Plot 10, the variability was also high across the plot. This variability highlighted the importance of using a blocked design, but, also the need to observe germination around the plot to reduce the likelihood that there is variability within the plot, not attributable to the treatments, which may invalidate the block for statistical analysis. This high variability across the block highlights that one or more of the factors affecting germination and seedling survival are changeable across small spatial scales. It is also possible that there is a limiting soil factor which only requires a small change to no longer be limiting. Certainly the variation across the block could not be attributed to climate, slope, aspect, seed predation or

herbivory. Levels of organic matter, soil moisture and soil compaction are all possibilities which further studies, beyond the scope of the current research, could examine.

Many investigators only monitor for 3-6 months and many studies extend only for about 6 months. If this experiment had been concluded at 6 months the results and recommendations, especially for Site 3, would have been very different (see Figures 4.3.2 and 4.3.6). The results show that the number of seedlings at 6 months, at these sites, does not reflect success of the revegetation in the longer term, and therefore gives very little valuable management information. For the long term success of a revegetation program, plants need to survive long enough to produce viable seed. Certainly some individual plants for some species in this study achieved this (see Section 4.6), the vast majority, however, did not.

4.4 Seed removal / loss: Sites 1, 2 and 3

4.4.1 Introduction

During many of the germination studies at the sites, observations were made of chewed seeds and evidence that seeds may be being moved around was found at Site 1 with a seedling growing up-slope from one of the study quadrats. In addition, several different kinds of ants have been observed at all three sites, and some species of ants in Australia are well known for moving and, in some cases, eating seeds (Buckley, 1982; Campbell, 1982). The aim of these seed removal studies was to provide an indication of the amount of seed movement occurring at the sites and the degree to which this may account for the low field germination rates observed.

If seeds are being removed from quadrats, it may be either to the side or to depth. If many seeds had simply been moved sideways outside of the quadrat area, then it is likely that some seedlings would have been observed in these areas. This was not generally the case, except for the single occurrence at Site 1.

As a pilot study of the amount of seed movement and the potential for removal, open caches of seeds were placed at Sites 1, 2 and 3 with the number of seeds remaining in the caches

recorded over time. The nature of the experimental design was qualitative, thus, no statistical hypotheses were tested. The aim of the studies was to provide some answers to the following questions:

i. Is seed removal occurring?

ii. If yes, to what degree?

iii. Is there a difference in the seed removal at each of the sites, between the species and/or between the cache locations?

iv. If there is a large difference in the level of seed removal between species, is this reflected in the germination rates observed?

v. If there is a large difference in the seed removal at the different cache locations, are there any site features which may explain this, e.g., proximity to remnant vegetation and subsequent less disturbed areas which may be a source of ants?

vi. Are there any signs of disturbance or damage to seeds remaining in the cache?

A removal study was initially conducted at Sites 1 and 2 in 1996, after low field germination rates were recorded during pilot studies, and ants were observed in many areas across the sites. The second pilot study was conducted at Sites 2 and 3 in 1998, after the watering and mulching experiment (see Section 4.3).

4.4.2 Materials and methods

Seed removal trials were conducted using ten seed caches at each site. The caches comprised of open plastic petri dishes, 85 mm diameter, wall of 6 mm, attached to the ground by a 10 cm nail pushed through the centre of the dish. A stake with coloured tape was used to mark the location of the dishes. The stakes were placed at a distance of 2 m from the dishes to reduce the risk that birds using the stake as a perch would be easily able to see the cache.

Each cache contained 10 seeds from each species, with the number of seeds remaining in the cache recorded after 1 week. The remaining seeds were collected and signs of interference recorded.

Only those species with seeds large enough to be counted, not readily wind dispersed and readily identified were used in the experiment to enable the seeds of each species to be counted. The seeds were treated in the same way as in the germination trials to negate any effects that the treatment of the seed may have on their attractiveness, or otherwise, to potential granivores. Species which were not tested because their small seed size made identification difficult and/or there was a greater risk they would be removed from the caches from wind were: *Chrysocephalum apiculatum*, *Melaleuca thymifolia* and *Ozothamnus diosmifolius*.

4.4.2.1 Seed removal: Sites 1 and 2

Two caches were assigned to each of the five topographic areas of each site. For each area, one cache was randomly assigned to the top third and the other to the bottom third of the batter, this generally represented being further away and closer to remnant vegetation.

In the Time 1 study installed in May 1996, the species used were: *Acacia linifolia*, *A. ulicifolia*, *Atriplex semibaccata*, *Bursaria spinosa*, *Daviesia genistifolia*, *D. ulicifolia*, *Dillwynia juniperina*, *Hardenbergia violacea*, *Indigofera australis*, *Kennedia rubicunda* and *Lomandra longifolia*. One of the other issues with choosing species is the similarity of the seeds of some species. This was the case in this study with *H. violacea* and *K. rubicunda*. In many cases I could visually distinguish these seeds, but, not all the time, so results from these two species were combined. It would have been possible to select seeds from the batches that I could readily identify, however, my selection may have proved a more or less attractive selection to the granivores, thus placing a bias on the study.

4.4.2.2 Seed removal: Sites 2 and 3

The Time 2 seed removal study at Sites 2 and 3 was established in February 1998, after the mulching and watering experiment was conducted at these sites (see Section 4.3). The species used were: *Acacia linifolia, Atriplex semibaccata, Bursaria spinosa, Calotis cuneifolia, Daviesia ulicifolia, Hardenbergia violacea, Indigofera australis* and *Lomandra longifolia.* The species were selected from the list of species used in the mulch and water experiment. This time, to remove the confusion between *H. violacea* and *K. rubicunda*, only *H. violacea* was used.

After the caches had been placed at Site 3, it was observed that there was very rapid interest in the caches by ants, and seeds were already being moved from the dishes, so seed removal was also recorded 1-2.5 hours after placement. For this time period, no direct comparison could be made between the dishes, as the time of placement was different for each dish and with active removal, 10 minutes could make a big difference in the amount of removal recorded. The caches were also left in place at Site 3 for 40 days to see if seed removal continued over time.

In the Time 1 seed removal studies at Sites 1 and 2, seeds found on the surface outside the caches. For the Time 2 removal studies seed within 200 mm of the caches was also recorded to provide a fuller picture of what was happening to the seed.

4.4.3 Results

Seed removal was clearly occurring. There were differences in the removal rates for the various cache locations, across the three sites and the different species. In this section, results are provided for each of the three sites, for each cache and for each species. Possible explanations for the results found are provided. For Site 3, results are also provided for the three monitoring times and observations made on interference with the seed.

There was no evidence that seed had been removed due to climatic conditions such as wind or rain as the lightest seed was *B. spinosa* and there were no more seeds of this species removed than the other species.

In the following sections I examine the removal of seed at each of the three sites after 1 week (Section 4.4.3.1), the removal of seed after approximately 2 hours, 1 week and 40 days at Site 3 (Section 4.4.3.2); and finally interference and seed movement at Site 3 (Section 4.4.3.3).

4.4.3.1 Seed removal per site and cache location after 1 week: Sites 1, 2 and 3

Seed removal from the caches in the Time 2 removal studies at Sites 2 and 3 was much higher than that for Time 1 Sites 1 and 2 (Figure 4.4.1). Average seeds remaining in the caches were: Time 1 Site 1 84%, Site 2 81%; and Time 2 Site 2 7%, Site 3 3%.

The removal rates in the Time 1 study at Sites 1 and 2 were much less than some previous studies in Australia have found, e.g., Andersen (1982). If seed removal constituted loss of seed, the removal rates would not be enough on their own to prevent successful germination.

The rates for the Time 2 study at Sites 2 and 3, however, were much higher and if removal from the caches related to removal rates in the germination experiments and removal equated to loss of seed viability and/or availability, then it would be expected that the germination rates would be a lot lower for the experiments at Sites 2 and 3. In fact they would very likely be zero. This was not the case, with Site 3 recording some of the highest germination rates observed for any of the field experiments. How can this be? It is possible that removal of seeds is via ants which are not eating the seeds, however, are doing something to the seeds that improves the germination success, as such ant activity and seed removal may actually represent a positive contribution to success of direct seeding. Seed removal rates at Site 2 in the Time 2 study were also very low, however, germination rates were generally low there. Interestingly, rates of seed removal from the caches after 1 week at Site 2 (Time 2) was less overall and for most species that that at Site 3, while the germination rates at Site 3 were much higher overall than at Site 2. As such, removal of seed from caches after 1 week is not a good indicator of germination success with these species.

Crawford *et al.* (1994) found that seed removal by ants of two *Lomandra* species increased the germination rate as the ants removed the pericarp, which increased the seed viability and

thus allowed more germination to occur. It should be noted that some seed was eaten and do would not be available for germination (see Section 4.4.3.4).

Seed removal at the three sites was quite varied between species with the highest removal being 100% for *D. ulicifolia* and *L. longifolia* at Site 3 (see Figures 4.4.2-4.4.9). For Sites 1 and 2 (Time 1) the species with the fewest seeds removed was *I. australis*, while for Site 2 (Time 2) it was *I. australis* and for Site 3 (Time 2) *A. linifolia*. At Sites 1 and 2 (Time 1), *A. linifolia* was the species with the most seeds removed.

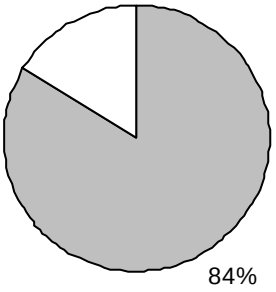


Figure 4.4.1.a Time 1 Site 1

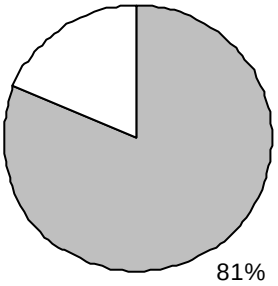


Figure 4.4.1.b Time 1 Site 2

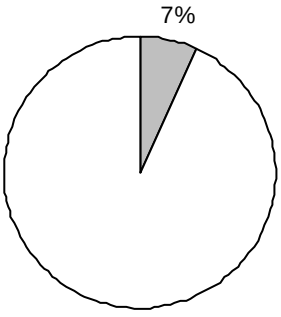


Figure 4.4.1.c Time 2 Site 2

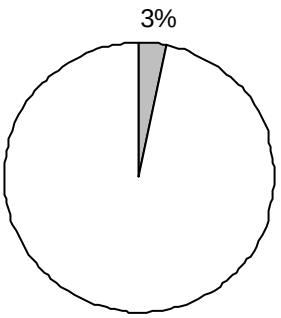


Figure 4.4.1.d Time 2 Site 3

Figure 4.4.1 Overall seed remaining in caches (stippled portion) and removed (open portion) after 1 week for the Time 1 and 2 studies

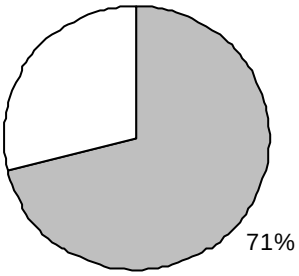


Figure 4.4.2.a Time 1 Site 1

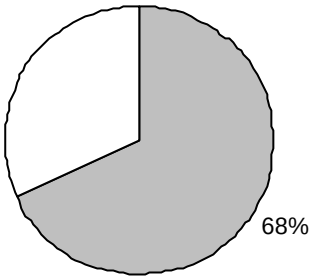


Figure 4.4.2.b Time 1 Site 2

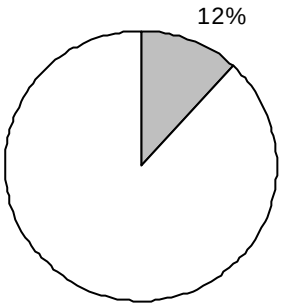


Figure 4.4.2.c Time 2 Site 2

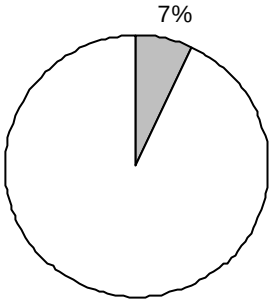


Figure 4.4.2.d Time 2 Site 3

Figure 4.4.2 Seed of *Acacia linifolia* remaining in caches (stippled portion) and removed (open portion) after 1 week for the Time 1 and 2 studies

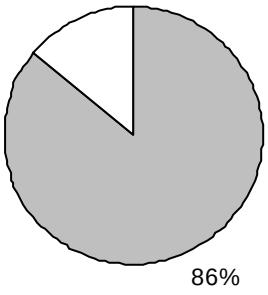


Figure 4.4.3.a Time 1 Site 1

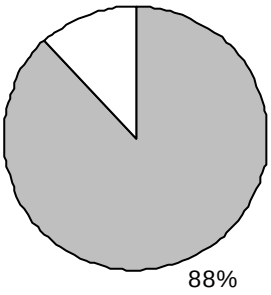


Figure 4.4.3.b Time 1 Site 2

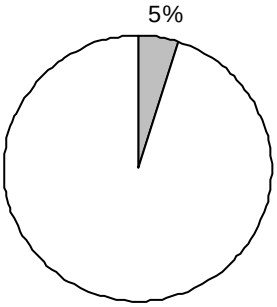


Figure 4.4.3.c Time 2 Site 2

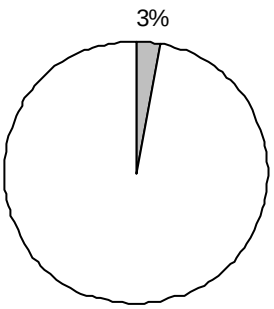


Figure 4.4.3.d Time 2 Site 3

Figure 4.4.3 Seed of *Atriplex semibaccata* remaining in caches (stippled portion) and removed (open portion) after 1 week for the Time 1 and 2 studies

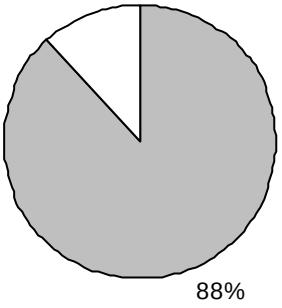


Figure 4.4.4.a Time 1 Site 1

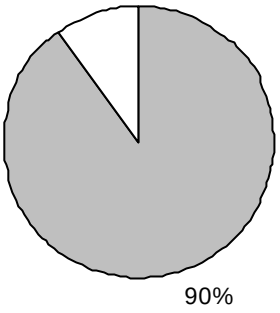


Figure 4.4.4.b Time 1 Site 2

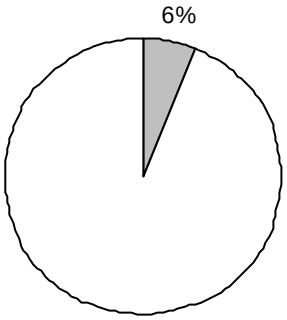


Figure 4.4.4.c Time 2 Site 2

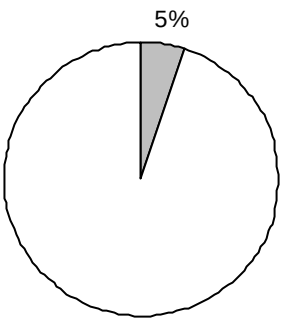


Figure 4.4.4.d Time 2 Site 3

Figure 4.4.4 Seed of *Bursaria spinosa* remaining in caches (stippled portion) and removed (open portion) after 1 week for the Time 1 and 2 studies

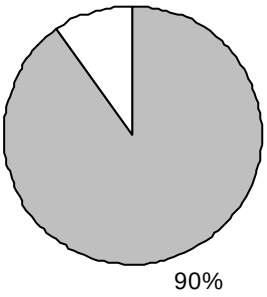


Figure 4.4.5.a Time 1 Site 1

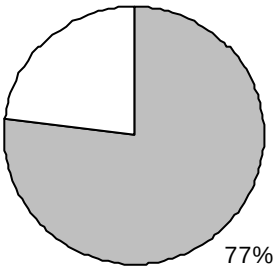


Figure 4.4.5.b Time 1 Site 2

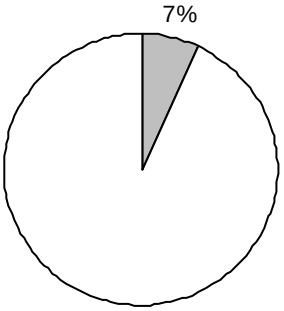


Figure 4.4.5.c Time 2 Site 2

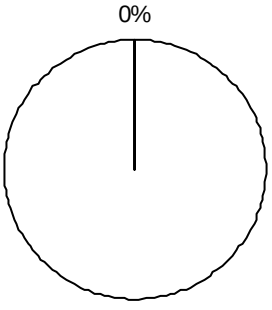


Figure 4.4.5.d Time 2 Site 3

Figure 4.4.5 Seed of *Daviesia ulicifolia* remaining in caches (stippled portion) and removed (open portion) after 1 week for the Time 1 and 2 studies

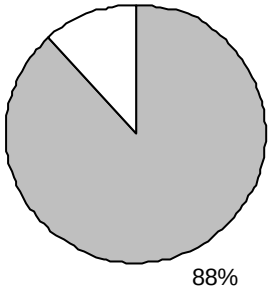


Figure 4.4.6.a Time 1 Site 1

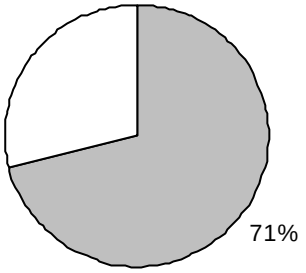


Figure 4.4.6.b Time 1 Site 2

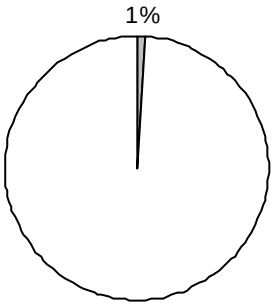


Figure 4.4.6.c Time 2 Site 2

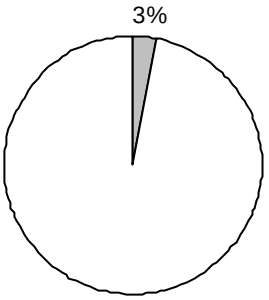


Figure 4.4.6.d Time 2 Site 3

Figure 4.4.6 Seed of *Hardenbergia violacea* (and *Kennedia rubicunda*; see Section 4.4.2) remaining in caches (stippled portion) and removed (open portion) after 1 week for the Time 1 and 2 studies

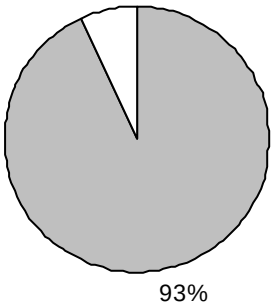


Figure 4.4.7.a Time 1 Site 1

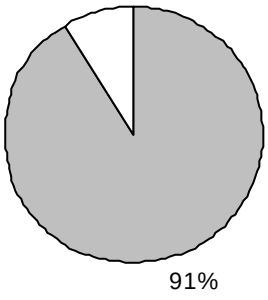


Figure 4.4.7.b Time 1 Site 2

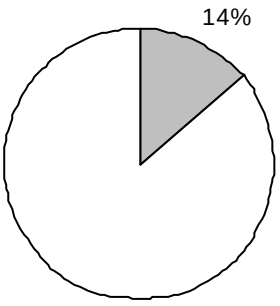


Figure 4.4.7.c Time 2 Site 3

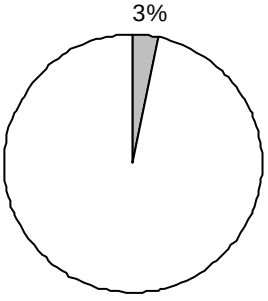


Figure 4.4.7.d Time 2 Site 3

Figure 4.4.7 Seed of *Indigofera australis* remaining in caches (stippled portion) and removed (open portion) after 1 week for the Time 1 and 2 studies

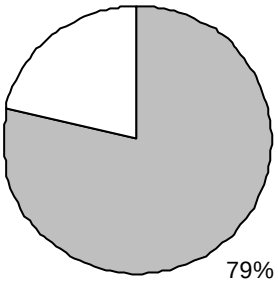


Figure 4.4.8.a Time 1 Site 1

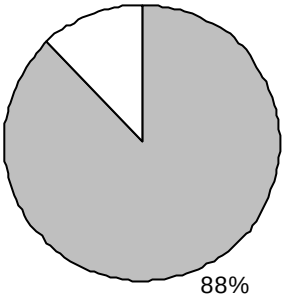


Figure 4.4.8.b Time 1 Site 2

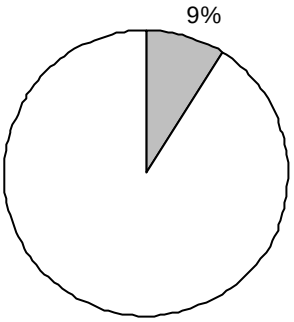


Figure 4.4.8.c Time 2 Site 2

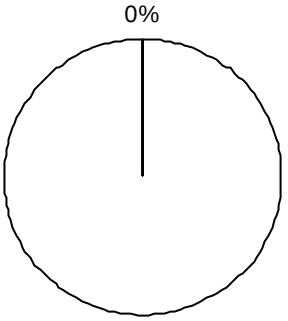


Figure 4.4.8.d Time 2 Site 3

Figure 4.4.8 Seed of *Lomandra longifolia* remaining in caches (stippled portion) and removed (open portion) after 1 week for the Time 1 and 2 studies

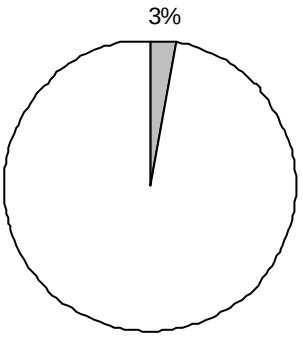


Figure 4.4.9.a Time 2 Site 2

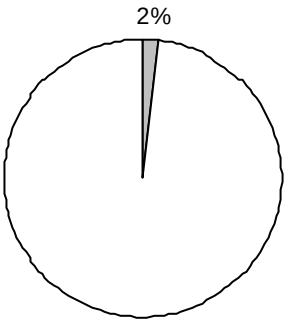


Figure 4.4.9.b Time 2 Site 3

Figure 4.4.9 Seed of *Calotis cuneifolia* remaining in caches (stippled portion) and removed (open portion) after 1 week in the Time 2 study at Sites 2 and 3

4.4.3.2 Seed removal after ~2 hours, 1 week and 40 days: Site 3

At Site 3, soon after placement of seed in the caches, ants were observed actively removing seeds. Therefore, early seed removed was counted with individual caches being counted between 1.5 and 2.5 hours after placement. If interest in the caches was even across the site it would be expected that the seeds remaining in the cache would decrease over time, regardless of which cache was being recorded. This, however, was not the case, with the cache recorded after 135 minutes actually having more seeds remaining than the cache recorded after 80 minutes (Figure 4.4.10).

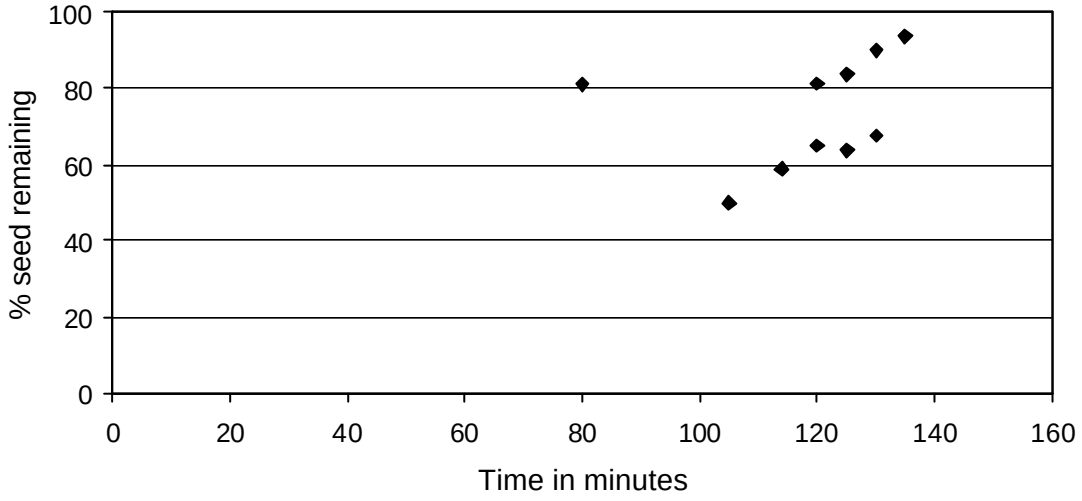


Figure 4.4.10 Site 3, early seed removal, percent seed remaining in each cache, and the time recorded

Seeds remaining within each cache continued to decline between 1 week and 40 days with average seed remaining after 1 week 3.25% (range of 0-12.5) and after 40 days 1.5% (range of 0-5).

Seed removal was the most rapid for *L. longifolia* with 23% of seeds remaining after the early period and 100% removed by 1 week (Figure 4.4.11). The lowest seed removal was for *A. linifolia* with 95% of seed remaining after the early time period and 7% after 1 week

with no decrease after 40 days. However, of the *A. linifolia* seeds remaining, most had their elaiosomes removed (see Section 4.4.3.3).

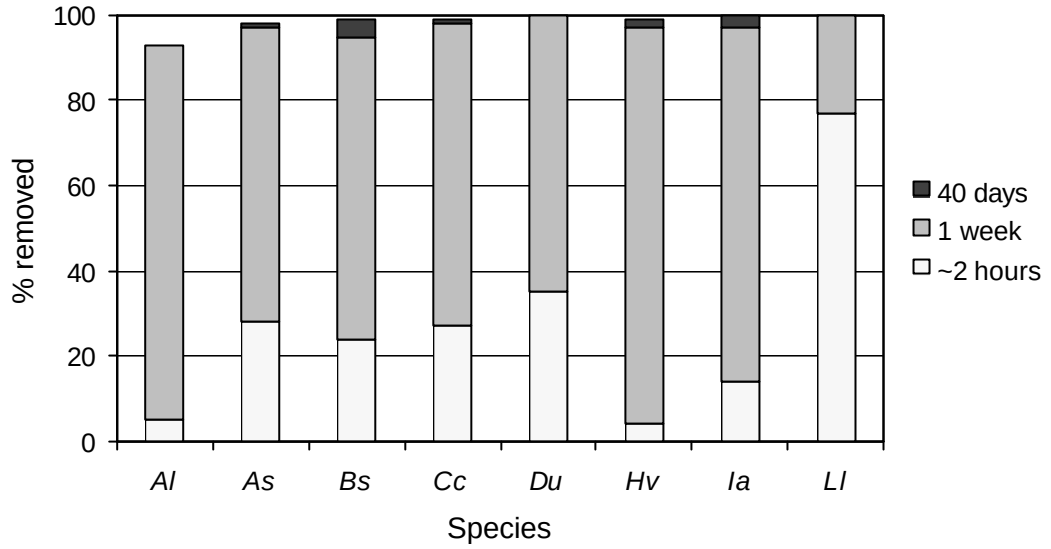


Figure 4.4.11 Site 3: percent seed remaining by species after ~2 hours, 1 week and 40 days

While there was very little difference between the removal rates after 1 week and after 40 days it should be noted that there were not many seeds left to be removed. With such high rates of seed removal, it would be interesting to know why some seeds were left. Some seeds were found on the soil surface surrounding the cache while many of the seeds that remaining in the caches had been interfered with (see Section 4.4.3.3).

4.4.3.3 Seed movement, interference and damage: Time 2 Sites 2 and 3

For the Time 2 seed removal study at Sites 2 and 3, observations were made on damage to the seed, the removal of elaiosomes and the presence of seed within 200 mm of the caches.

Obvious interest in, and damage to, some seeds was recorded at the initial observation time at Site 3 between 1.5 and 2.5 hours. This included active removal of an *A. linifolia* seed to under Cache 2 and vigorous defence of the seeds by small black ants when the observations were made. At Cache 4, small black ants started moving the seeds within 5 minutes of

placement, the main interest seemed to be in the *A. linifolia* and then *D. ulicifolia* and *H. violacea*. At Cache 6, one *D. ulicifolia* seed was found just outside (within 50 mm) the cache. At Cache 7, one *L. longifolia* seed was found ~200 mm from the cache. For Cache 8, one seed each of *B. spinosa, D. ulicifolia, I. australis* and *L. longifolia*, were found within 100 mm of the cache. From these observations, I surmise that the primary source of early seed removal at Site 3 was by small black ants and that some of the seed is not being moved very far.

After one week the majority of seed had been removed from the caches (Figure 4.4.12), some seeds had been damaged, some had their elaiosomes removed and some were found in close proximity to the caches (Table 4.6). Small black ants were again found around all of the caches.

The numbers of seed on the soil surface within 200 mm of each cache was recorded to provide an indication of whether removal from the cache may mean loss of seed from the area. These recordings were qualitative in nature for 3 reasons:

i. Some seed may have been buried;

ii. There were cracks where smaller and/or thinner seed, e.g., *B. spinosa*, could fall;

iii. Seed from *A. semibaccata* was difficult to see outside the cache as it readily blended in with the soil.

After 1 week seed remaining within the caches ranged from 1.3 to 11.3% at Site 2 and 0 to 12.5% at Site 3; and within 200 mm ranged from 0 to 11.3 at Site 2 and 2.5 to17.5% at Site 3. After 40 days seeds remaining in the caches at Site 3 ranged from 0 to 6% and within 200 mm ranged from 0 to 10%.

These observations show the seed removal from the caches in a different light. For *A. linifolia* and *H. violacea*, between 20 and 80% of the seeds removed from the caches after 1 week did not represent loss of the seed from the area, as the seed was simply moved outside the cache, mostly with elaiosomes missing. In addition, removal of the elaiosome may result in damage to the hard seed coat, thereby allowing water into the seed and breaking dormancy.

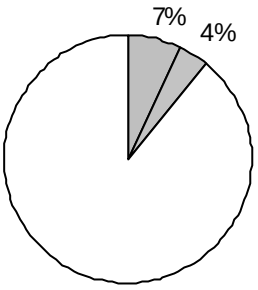


Figure 4.4.12.b Site 2 1 week

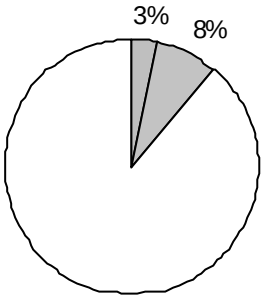
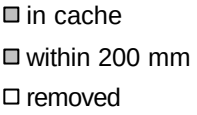


Figure 4.4.12.b Site 3 1 week



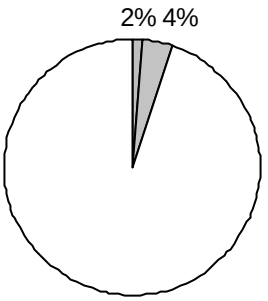


Figure 4.4.12.c Site 3 40 days

Figure 4.4.12 Seed within the cache (stippled portion), within 200 mm of the cache (hatched portion) and removed (open portion), for the Time 2 study at Sites 2 (after 1 week) and 3 (after 1 week and 40 days)

Some seeds at Site 3, however, were partly eaten or hollowed, so would not be available for germination. These were:

i. *A. linifolia* - 1 hollowed seed at Cache 2;

ii. *I. australis* – 1 hollowed seed at Cache5, 1 partly chewed at Cache 10;

iii. *D. ulicifolia* – 1 hollowed seed outside Cache 8.

4.4.4 Discussion

Seeds were removed from all caches at all three sites and included every species tested. The degree to which seed removal occurred varied between the sites, species and cache locations. Overall seed removal after 1 week was far higher in the Time 2 study at Sites 2 and 3 with just 7% and 3% of seed remaining in the caches compared to Time 1 Sites 1 and 2 with 81 and 84% respectively. The stark difference between the removal rates for these 2 studies could be attributed to the time of year with the Time 1 study conducted in May and the Time 2 in February/March. Ants tend to be more active in the warmer months, as in the second study, and less active in the colder months, as in the first study.

The similarity of the removal rates for Sites 1 and 2 was very interesting as landfilling was completed at Site 1 two years earlier that Site 2. Time since completion does not appear to be a factor in seed removal for these two sites.

It is interesting to note that Cache 10 at Site 3 was one of the closest to remnant vegetation, yet had the lowest seed removal after 2 hours. This would indicate that ants are not moving onto the areas from nests in areas with remnant vegetation, rather there are already nests on the landfilled areas.

Table 4.6 Damage to and movement of seed in the Time 2 seed removal study at Site 2 (1 week) and Site 3 (1 week and 40 days) (see Section 4.4.3.2). Only those species with seed found within 200 mm of the cache, or had elaiosomes removed, are listed. The numbers in brackets are the number of seeds without elaiosomes.

		Site 2: 1 week		Site 3: 1 week		Site 3: 40 days	
Cache	Species	In cache	200 mm of cache	In cache	200 mm of cache	In cache	200 mm of cache
1	**Total**	**9**	**9**	**10**	**10**	**4**	**8**
	A. linifolia	1 (1)	3 (3)	2 (0)	5 (4)	2 (2)	2 (2)
	H. violacea	0	6 (6)	2 (0)	5 (2)	0	6 (6)
2	**Total**	**6**	**0**	**2**	**4**	**2**	**2**
	A. linifolia	1 (0)	0	1 (0)	1 (1)	1 (1)	0
	H. violacea	1 (0)	0	0	2 (2)	0	2 (2)
3	**Total**	**8**	**6**	**0**	**9**	**0**	**2**
	A. linifolia	0	2 (2)	0	5 (5)	0	1 (1)
	D. ulicifolia	1 (0)	1 (1)	0	1 (0)	0	0
	H. violacea	3 (0)	2 (1)	0	2 (2)	0	0
	I. australis	0	1	0	1	0	1
4	**Total**	**2**	**3**	**6**	**10**	**5**	**5**
	A. linifolia	0	0	2	5 (5)	2 (2)	1 (1)
	H. violacea	1 (0)	3 (0)	1	4 (4)	1	4 (4)
	I. australis	0	0	1	1	0	0
5	**Total**	**8**	**7**	**2**	**13**	**2**	**4**
	A. linifolia	4 (0)	1 (1)	2 (0)	5 (5)	2 (2)	2 (2)
	B. spinosa	0	2	0	0	0	0
	H. violacea	1 (0)	4 (4)	0	8 (8)	0	2 (2)
6	**Total**	**9**	**0**	**1**	**8**	**0**	**3**
	A. linifolia	1 (1)	0	0	3 (3)	0	1 (1)
	H. violacea	4 (4)	0	0	5 (5)	0	2 (2)
7	**Total**	**5**	**3**	**1**	**7**	**0**	**4**
	A. linifolia	1 (0)	1 (1)	0	4 (4)	0	2 (2)
	H. violacea	1 (1)	1 (1)	0	3 (3)	0	2 (2)
	I. australis	1	1	0	0	0	0
8	**Total**	**1**	**0**	**0**	**14**	**0**	**10**
	A. linifolia	0	0	0	7 (7)	0	6 (6)
	H. violacea	1 (0)	0	0	7 (7)	0	4 (4)
9	**Total**	**1**	**1**	**0**	**10**	**0**	**5**
	A. linifolia	1 (0)	0	0	5 (5)	0	2 (2)
	H. violacea	0	1 (0)	0	5 (5)	0	3 (3)
10	**Total**	**2**	**3**	**1**	**2**	**0**	**0**
	B. spinosa	0	0	1	1	0	0
	H. violacea	1 (0)	3 (0)	0	1 (1)	0	0

The seed caches differed from the seeds sown on the ground in three main ways. Firstly, the seeds were not covered in any way in the cache, whereas in the germination studies the ground was lightly raked before and after seed sowing, resulting in the seed being lightly covered by soil (see Section 4.3.2). Secondly, the caches had a side of 6 mm which was to stop the seed from simply rolling out or being blown out by light winds. Thirdly, the cache was made of plastic, and therefore, seeds could not be removed straight down into the soil from the cache, which would have been possible in the germination studies.

The wall of the cache did not appear to limit seed removal as *A. linifolia* had the largest and heaviest seeds (Table 2.4) and many of these seeds were removed. I observed small black ants removing seeds from Caches 2 and 4 at Site 3.

These seed removal studies proved to be fascinating and provide some interesting insights on what may be happening to the seeds at the Sites. Many more questions have now been raised and more research on this area, beyond the scope of the current study, would most likely prove to be very fruitful.

4.5 Herbivory

With the high levels of herbivory observed during the planting experiment (see Section 3.4), I hypothesised that marking the plants, to make them easier to find, increased the levels of herbivory observed by making the plants more noticeable to herbivores. I installed a planting experiment at Site 2 to test this hypothesis. Three treatments were used in the experiment: Unmarked; Marked; and Marked plus Tree Guard. The Tree Guard treatment was intended to exclude herbivory. Six species were used: *Acacia linifolia*, *Bursaria spinosa*, *Dillwynia juniperina*, *Indigofera australis*, *Kennedia rubicunda* and *Lomandra longifolia*. For each species, 15 plants were installed in each of the treatments. The plants used were the same size and grown in the same was as those used for the landfill planting experiment (see Section 3.3.3).

If marking the plants increased herbivory, then it would be expected that the plants in the Marked treatment would show higher herbivory levels than those in the Unmarked treatment.

This experiment was established off the landfilled area to keep it away from the main planting experiment (see Section 3.4), and to provide plants for observations of root growth (see Section 4.6).

Three problems were encountered with this experiment, which prevented statistical comparison between the three treatments.

i. Firstly, there was a number of incidents of vandalism at the Site where canes were taken, both from the Marked treatment and from the Tree Guards. The vandalism affected 5 plants in the Marked treatment, and 11 in the Tree Guard treatment.

ii. Secondly, there were problems with goats on the Site, which reached inside the tree guards, eating the plants which were thought to be protected from herbivory. This affected at least two of the plants in the Tree Guard treatment.

iii. Thirdly, for the two months after planting, just 37 mm of rainfall fell in the area (Bureau of Meteorology, 2005). This dry period resulted in the deaths of many of the plants, allowing no comparison of the Marked and Unmarked plants.

Four months after planting there was a total of 34 plants left alive, just 11% of those originally planted. For each of the treatments the numbers surviving were: Unmarked 9; Marked 11; and Tree Guard 14. *L. longifolia* had the highest survival rates overall, which was the same result as for the planting experiment on the landfill (see Section 3.4). The numbers of each species surviving in each treatment are provided in Figure 4.5.1.

With such high death rates, statistical comparison between the treatments was not possible. This experiment did, however, emphasise the importance of rainfall, and subsequent soil moisture, as a limiting factor in the survival of new plants at the site.

Despite the problems encountered with this experiment, it proved useful in a number of ways:

i. One of the factors effecting plant survival at this Site was vandalism;

ii. Low rainfall, with subsequent low soil moisture, soon after planting, is a greater limiting factor to revegetation than herbivory;

iii. With the low numbers of the plants that survived, marking certainly did not increase the rates of herbivory, however, it seemed to increase the level of vandalism;

iv. Plant survival was higher for the plants with tree guards for 3 of the 6 species: *A. linifolia*, *D. juniperina* and *K. rubicunda*;

v. Surviving plants were used in the plant removal experiment (see Section 4.6).

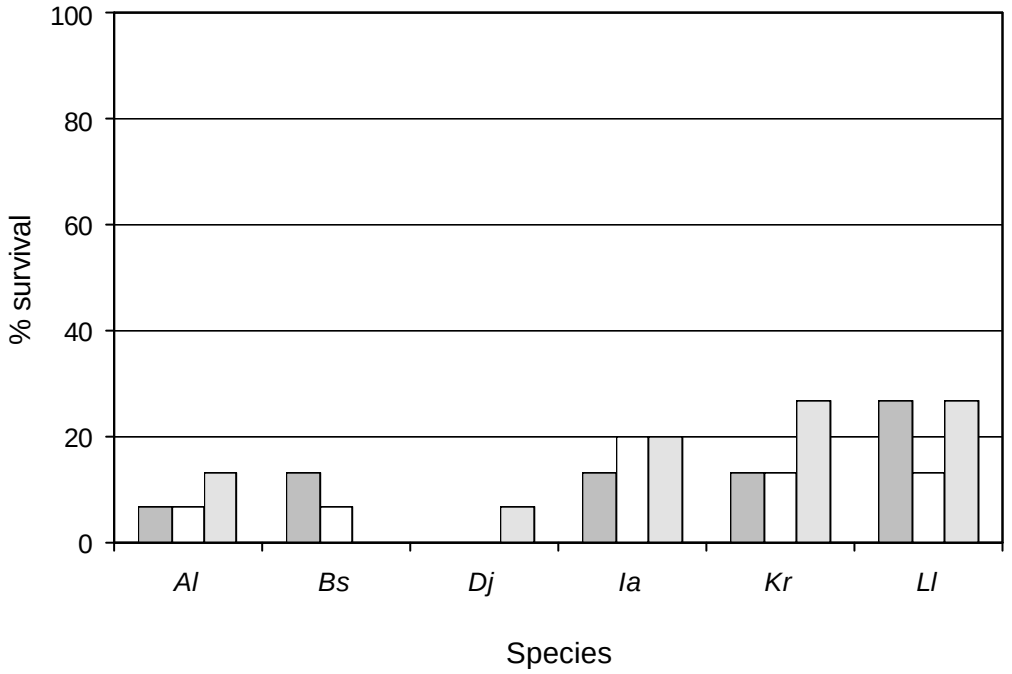


Figure 4.5.1 Herbivory trial Site 2: Percentage survival for each species and treatment: Marked – stippled bar; No treatment – open bar; and Tree guard – thatched

4.6 Shape, size and general characteristics of the root systems

4.6.1 Introduction

Research has shown that dead roots can provide a path for water to enter soil (Mitchell *et al*., 1995). If the roots of the plants in the current study grow down through the cap, then the purpose and requirement of the cap to separate the wastes from the surrounding environment

and prevent the ingress of water, may be compromised. It is important therefore, to know whether roots will grow into the cap, and, if so, how far.

Previous excavation research on clay capped landfills by Robinson, Handel and others (Robinson & Handel, 1995; Handel *et al*., 1997), found that many roots, including tap-roots, were deformed and grew parallel to the clay liner (see Section 1.4.3). The landfill sites I examined were different in three broad ways: there was no distinct boundary of different soil types between the cap and the cover material; the plants species examined were different; and the species used grew naturally in the same heavy clay soils that were used for the capping. With the differences between my study and these previous excavation studies, one of my aims was to determine if the results of my study would support the findings of this previous work.

The clay liners on landfills restrict root growth through several ways: physical impedance; low permeability, resulting in low soil oxygen and moisture (see Section 1.3.2); and, at some sites chemical characteristics (Robinson & Handel, 1995). Some plant species naturally grow in hard, low permeability soils; these conditions often occur in the areas around clay capped landfills as that can be one of the criteria for site selection. The three sites I examined, were located in areas of heavy clay soils (see Sections 1.6 and 2.2), and part of the selection criteria for the experimental species was that they were known to grow in the region where the heavy clay soils were found (see Section 2.2). There was, however, little to no information available about their root systems, including whether they formed tap-roots, or how the root systems respond in different conditions.

Previous work has shown that for some species mycorrhizal infection of the roots is necessary for good health and that these mycorrhizae are not always present on highly disturbed sites, such as the landfills studies here, and can have limited dispersal (Allen, 1991; Parsons *et al*., 1998). Roots were examined for evidence of fungal infection in the field, and samples collected which are available for future research.

Many aims of the plant removal experiment were not achieved for a variety of reasons. The two main problems encountered were: the low rate of plant survival; and the heavy, plastic nature of the clay soils. Each of the original aims and the problems encountered, are presented below:

i. One of the aims of the experiment was to compare species grown at two sites (Sites 1 and 2), at several different ages. Due to the high death rates observed across all species, sites and experiments (see Section 3.4), this was not possible.

ii. Permeability of the soils around the plants, and the paths water was taking into the soil, was going to be determined by placing infiltration tubes around each plant. This could not be achieved due to the plastic nature of the clay soils: once wet, the soil became very sticky, making excavating the plant almost impossible.

iii. The depth and lateral spread of each root system was going to be recorded. In many cases this was not practical due to the hard plastic nature of the clay soils: this not only made the digging physically hard, it was also difficult to dig without damaging/losing roots.

iv. Permeability and bulk density were going to be determined for the soil within and immediately below the root systems, by collecting relatively undisturbed cores of soil material. This proved virtually impossible due to the very hard nature of the soils, and so was not completed.

Taking into consideration the problems encountered with the poor plant survival rates and the heavy plastic nature of the soil, a new series of aims was developed for the plant excavation experiment:

i. To provide qualitative information about the root systems from as many of the experimental species as possible, from plants growing on all three experimental sites, on and off the landfill, and grown from seed and planted;

ii. To determine the presence or absence of tap-roots in each of the species;

iii. To identify differences between the plants growing on or off the landfilled area;

iv. To identify differences in plants grown from seed or planted;

v. To observe if the above ground size of the plant was reflected below ground;

vi. To record the direction of root growth in order to see if this research replicated previous research where roots were deformed and grew laterally to the cap;

vii. To record evidence of mycorrhizal infection;

viii. To provide a basic description of the roots for each of the species excavated.

4.6.2 Materials and methods

Plants were excavated from all three sites, from planted and directly sown, both on and off the landfilled area. As already stated in the introduction, due to the high mortality across all the experiments, not many plants were available for removal. In most cases, the plants excavated on the landfill areas were the only ones available. To enrich the data set, several plants from species not used in the experiments, were also excavated.

Plants from nine species were excavated across each of the three sites: *Acacia linifolia*, *A. falcata*, *A. fimbriata*, *Atriplex semibaccata*, *Daviesia genistifolia*, *Hardenbergia violacea*, *Indigofera australis*, *Kennedia rubicunda* and *Lomandra longifolia*. For most plants only half of the root system was exposed. This was a result of time constraints, and the aim to leave the plants alive in the field for future experiments.

For each plant, general information relating to plant size, health, level of grazing and appearance was recorded (see Section 3.3.2 and Sheet B4, Appendix B). In addition, the presence, thickness and type of mulch; and the location and history of the plant were recorded e.g., on or off landfill, planted or grown from seed.

The rest of the information recorded, related to the root system and the associated soil.

i. General root description, e.g., white, yellow, woody;

ii. Presence of a taproot;

iii. Depth of the roots, where it was not possible to excavate the full depth of the roots a note was made that roots were continuing;

iv. Lateral spread of the root system, again, where it was not possible to excavate the roots to their full extent no note was made that the roots were still continuing, and the thickness of the root when excavation ceased;

v. A description of the shape and spread of the root system, including how evenly distributed;

vi. Basic presence of features indicating mycorrhizal infection, such as nodules and white masses or streaks adjacent to the roots, was recorded. Where feasible samples were collected of nodules or white "fungal" masses and preserved in 50% ethanol solution (Gardner, 1975) for examination in future research. Root samples from each plant excavated were also collected and preserved in 50% ethanol solution (Gardner, 1975) for examination in future research;

vii. Basic description of the soil type, plus collection of a sample from within the roots system.

Excavation was undertaken using picks and brushes. As the root system was exposed, general notes were made on the roots, their lateral spread, depth, presence and size of any taproot, and shape (see Sheet B4, Appendix B).

4.6.3 Results

Most of the results presented are descriptive due to the qualitative nature of the results and the observations made.

The ages of the plants excavated ranged from 15-52 months (Table 4.7). The wide range in ages was spread across the species and sites. An approximate age, based upon field notes and photographs, was provided for those plants grown from seed at the site and not sown as part of the experiments. The planted specimens were 1-3 months old at the time of planting. There was no clear link between the age of the plants and their size.

At the time of the excavation, all but one of the plants had only minor grazing, with tips removed or holes in the leaves (see Section 3.4.2.2; and Table 4.7). For one plant, from *A. falcata*, at Site 3 on the landfilled area, half of the plant was lying on the ground near the plant. Most of the plants that had been planted were covered by tree guards, the plants

grown from seed at the site were not. So, whilst herbivory has been found to be a limiting factor to the growth and survival of plants at these sites (see Section 3.4.4), it has not affected all plants.

All of the plants were healthy with bright green leaves or showed some drooping or yellowing of leaves (see Section 3.4.2.2, and Table 4.7). With the tough conditions that these plants were growing in (see Sections 2.2.2; and 3.4.3), it is quite likely that any plants which were showing greater signs of stress, would have already died.

Out of the 52 plants excavated, 19 had evidence of reproductive structures at the time of excavation (Table 4.7). The presence of reproductive structures occurred across all three experimental sites, from seeded or planted specimens and from both on and off the landfilled areas and involved 7 of the 9 species examined. The two species which did not have any evidence of reproductive structures on any of the plants excavated were: *Atriplex semibaccata* and *Indigofera australis*. Individual plants of these two species had, however, produced flowers and seed during the course of the other studies.

Ten of the excavated plants were found to have taproots, for a further four of the plants, excavation was insufficient to determine if a tap-root was present (Table 4.7). For three species, a taproot was present in some cases and not others: *A. linifolia*; *A. falcata*; and *K. rubicunda*. In many cases the taproot split and or deformed and grew laterally, this replicated the results found by Handel *et al*. (1997). The one species, with several plants excavated, which showed no evidence of a tap-root was *L. longifolia*.

For several of the plants growing on the landfilled areas, roots were found to be growing upwards. Gilman *et al*. (1981b) found that significantly more roots of plants growing on landfilled areas grew upwards than those growing on non-landfilled areas. They also found that significantly more roots were growing upwards for plants growing on a vented part of the landfill compared to a plastic lined part of the landfill.

Table 4.7 Plant removal summaries

Species	Site	On or off landfill	Planted or from seed	Age at removal (months)	Height[4] (cm)	Grazing[5] $_{TG}$ if guard present	Health[6]
Acacia linifolia	1	On	Planted	35	100	0_{TG}	1
	2	On	Seed-exp	41	240	0	1
	2	Off	Planted[2]	22	350	2_{TG}	1
Acacia falcata	2	Off	Seed[1]	55[3]	220	2	1
	3	On	Planted[2]	30	145	2	1
	3	On	Planted[2]	30	40	3	2
	3	On	Planted[2]	30	95	2	1
Acacia fimbriata	1	On	Seed[1]	50[3]	250	2	1
	1	On	Seed[1]	60[3]	210	2	1
	1	On	Seed[1]	60[3]	300	2	1
Atriplex semibaccata	2	On	Planted	30	17	0_{TG}	1
Daviesia genistifolia	3	On	Seed-exp	35	21	0	1
	3	On	Seed-exp	35	23	0	1
Hardenbergia violacea	2	On	Planted	28	90	0_{TG}	1
	2	Off	Seed[1]	45[3]	140	2	1
	2	Off	Seed[1]	60[3]	300	0	1
	3	On	Seed-exp	23	180	0	1
	3	Off	Planted	30	120	2	1
	3	Off	Seed[1]	30[3]	140	2	1
Indigofera australis	2	On	Planted	29	43	0	1
	2	Off	Planted	22	70	1	2
	2	Off	Planted	40	120	0	1
Kennedia rubicunda	1	On	Planted	35	260	2_{TG}	1
	2	Off	Planted	40	650	2	1
	3	On	Seed-exp	23	210	2	1
	3	On	Seed-exp	35	250	2	1
	3	On	Seed-exp	18	500	2	2

1 Seed either from natural regeneration or as part of general revegetation works;

2 Planted as part of general revegetation on site;

3 Age a guesstimate based upon when capping and revegetation works were conducted;

4 For a description of height measurement (See Section 3.3.2);

5 For a description of the grazing scale (see Section 3.3.2);

6 For a description of the health scale (see Section 3.3.2);

Reproduction	Tap root present: depth (mm)	Depth of main roots (mm) [7]	Lateral spread of main roots (mm) [8]	Max root diameter (mm)	Nodules	White fungal mass	Label
Flower buds	No	170	300	3	Yes	ND	HPAl051
Flowering	Yes	100+	500	10	Yes	ND	SFAl720
Flowering	[9]	[9]	[9]	[9]	Yes	ND	SFAl800
Flowering	[9]	[9]	300	25	Yes	ND	SFAf800
	No	120	60	12	Yes	ND	LDAf901
	Yes	125	50	8	Yes	ND	LDAf902
	No	90	60	10	Yes	ND	LDAf903
Seed pods		250	1000	28	Yes	Yes	HPAf050
	No	160	1550	40	Yes	ND	HPAf051
Has seeded	Yes	50+ (35)	[9]	3.5	ND	ND	HPAf052
	No	100	360	3.5	ND	ND	SFAs500
Seed pods	Yes	100	30	5	ND	ND	LDDg901
	Yes	60	20	3	ND	ND	LDDg902
Seed pods	No	180	240	5	Yes	ND	SFHv651
	Yes	[9]	400	8	ND	ND	SFHv800
	Yes	[9]	[9]	[9]	Yes	ND	SFHv801
	Yes: 130	1300	120	10	ND	ND	LDHv900
Seed pods	Yes	130	300+ (40)	5	Yes	ND	LDHv950
Seed pods	Yes: 130+	130+	750: 350	8	ND	ND	LDHv951
	No	150	50	6	Yes	Yes	SFIa600
	No		250: 400	3	ND	ND	SFIa800
		50+	40+		Yes	ND	SFIa801
Seed pods	No		40	5	Yes	ND	HPKr057
Seed pods	[9]	125+	600+ (3)	50	Yes	ND	SFKr800
Seed pods	No	180	350	2.5	Yes	ND	LDKr900
Seed pods	Yes	130	310+ (2)	18	Yes	Yes	LDKr901
	No	100	220	3	Yes	ND	LDKr902

7 Depth of main roots, if a single root continued below this level it is noted afterwards, a + sign shows that the roots continued below the depth of the excavation in which case the diameter of the root is provided in parentheses;

8 Lateral spread of the bulk of the roots, if one or two roots extended beyond the main then their length is noted afterwards, a + sign shows that the roots continued past the area excavated in which case the diameter of the root is provided in parentheses;

9 Only part of excavation carried out.

Table 4.7 Plant removal summaries, continued, *Lomandra longifolia*

Species	Site	On or off landfill	Planted or from seed	Age at removal (months)	Height[4] (cm)	Grazing[5] TG if guard present	Health[6]
Lomandra longifolia	1	On	Planted	51	500	0_{TG}	2
	1	On	Planted	51	630	0_{TG}	1
	1	On	Planted	51	610	0_{TG}	1
	1	On	Planted	51	700	0_{TG}	1
	1	Off	Planted[2]	52	900	0	1
	1	Off	Planted[2]	52	500	0	2
	2	On	Planted	30	400	0_{TG}	2
	2	On	Planted	28	330	0_{TG}	2
	2	On	Planted	29	410	0_{TG}	1
	2	On	Planted	29	220	0_{TG}	1
	2	On	Planted	31	570	0_{TG}	1
	2	On	Planted	29	380	0_{TG}	1
	2	Off	Planted	22	620	0_{TG}	1
	2	Off	Planted	40	600	0_{TG}	1
	2	Off	Planted	40	950	0_{TG}	1
	3	On	Planted[2]	15	400	0_{TG}	1
	3	On	Planted[2]	15	500	0_{TG}	1
	3	On	Planted[2]	27	150	0	1
	3	On	Planted[2]	27	300	0	1
	3	On	Planted[2]	18	320	0_{TG}	1
	3	On	Planted[2]	18	350	0_{TG}	1
	3	Off	Planted[2]	18	500	0_{TG}	1
	3	Off	Planted[2]	18	450	0_{TG}	1
	3	Off	Planted[2]	17	330	0_{TG}	1
	3	Off	Planted[2]	17	240	0_{TG}	1

Reproduction	Tap root present: depth	Depth of main roots (mm) [7]	Lateral spread of main roots (mm) [8]	Max root diameter (mm)	Nodules	White fungal mass	Label
	No	120	140	2	ND	ND	HPLl051
Flowered	No	160	400	2	ND	ND	HPLl052
Seeds	No	160	400	2	ND	ND	HPLl053
	No	100	70	2	ND	ND	HPLl054
	No	150	170: 360	2	ND	ND	HPLl300
	No	140	150	2	ND	ND	HPLl301
	No	180	250	3	ND	ND	SFLl514
	No	150	190	3	ND	ND	SFLl660
Flowered	No	160	140	3	ND	ND	SFLl607
	No	90	140	2	ND	ND	SFLl714
	No	120	150	2	ND	ND	SFLl510
	No	150	260	2.5	ND	ND	SFLl550
	No	180	450	2	ND	ND	SFLl800
	No	110	250	2	ND	ND	SFLl801
Flowered	No	120	700	3	ND	ND	SFLl802
	No	220	160	2	ND	ND	LDLl900
	No	170	140: 300	2	ND	ND	LDLl901
	No	70	170	1	ND	ND	LDLl902
	No	120	170	1	ND	ND	LDLl903
	No	175	350	2.5	ND	ND	LDLl904
Flower stalk	No	180	250	3	ND	ND	LDLl905
	No	170	350	2	ND	ND	LDLl950
	No	140	260	2	ND	ND	LDLl951
	No	130	400	3	ND	ND	LDLl952
	No	100	200	3	ND	ND	LDLl953

The highest recorded rooting depth out of all the excavations, was 22 cm for *L. longifolia* growing at Site 3 on the landfill, which had been growing on site for 15 months (Table 4.7). For five of the planted plants, the root ball did not extend to the base of the original planting soil. Several of the plants excavated had vertical roots which turned and grew laterally.

The lateral spread of the roots was often difficult to determine due to the problems already discussed with the plant removal. The spread of the plant roots was very variable between species, and within species (Table 4.7). The differences in spread could not always be explained by age, nor by being grown on or off the landfilled area.

Nodules were found with the roots of 20 of the 52 plants excavated. The most commonly effected were the Acacias – 3 out of 3 *A. linifolia*; 4 out of 4 *A. falcata*; and 3 out of 4 *A. fimbriata*. Many plants from the Fabaceae family were similarly effected – 3 out of 6 *H. violacea*; 2 out of 3 *I. australis*; and all 5 *K. rubicunda*. Three species showed no signs of nodulation – *A. semibaccata*; *D. genistifolia* (also a member of the Fabaceae family); and *L. longifolia* (Table 4.7). For four of the plants which had nodules, they were only found in the original planting soil and not in the surrounding clay.

White fungal masses were only observed at three of the plant excavations: *A. fimbriata* at Site 1 grown from seed on the landfill area; *I. australis* at Site 2 planted on the landfill and *K. rubicunda* sown on the landfill (Table 4.7). In the case of both the *A. fimbriata* and *K. rubicunda* other plant excavations in similar conditions at the same sites did not have evidence of white fungal masses.

4.6.4 Discussion

Roots did not penetrate into the cap for any of the species or individual plants examined. As per previous research (Robinson & Handel, 1995; Handel *et al*., 1997) roots, including tap-roots of plants growing on the landfill were often found to be deformed and growing laterally. Many of the plants also had very small root systems compared to the above ground growth. This could easily explain the poor survival of many of the plants as a small root system would be susceptible to drying out in the low rainfall periods which are common in this area (see Section 2.1.1).

Size of the plants excavated was variable with no observed correlation between either size and age, or above and below ground size. The main correlation with size was found to be presence on or off the landfill with plants off the landfill tending to be slightly larger. This size variation was the only difference determined between these plants. During excavation it was noted that for some species, e.g., the roots of the plants on the landfill seemed sparser than those growing off the landfill. This proved to be very difficult to quantify in the field, especially where fine roots were involved which were frequently torn during the excavation due to the hard heavy nature of the clayey soils.

The variable presence of nodules and white fungal masses around the roots was very interesting, as was the observation that for some plants nodules were only found in the original planting soil, they had not spread into the heavy clay soils present at the sites. If mycorrhizal infection is important for successful establishment, as has been argued in other landfill studies (e.g., Parsons *et al*., 1998), then these kinds of limitations may prove to be important. More research into this should prove to be fascinating.

My research also helped to illustrate why the root systems of plants growing in heavy clay soils have not been well studied – it is a matter of practicality, digging up the plants without doing any damage and/or while keeping all features intact for observation is extremely difficult. There are no simple ways around this. For many hard soils simply wetting can make the soil easier to work, with these heavy clays however, they then become extremely sticky and if possible, even harder to work. Using water to wash away the soil may be one option if adequate drainage away from the work area is available.

4.7 Factors limiting germination and plant survival

As in the earlier pilot studies, both germination, and seedlings and plant survival were very limited in most cases at the field site. There were, however, a few exceptions to this, providing some very intriguing results and illustrating just how complicated and multi-factored revegetation is.

In the following chapter I review the study as a whole, provide an overview of the limitations and lessons, and discuss how these studies fit in with the management of landfill sites and the revegetation of degraded sites in general.

Chapter 5
Conclusions and recommendations

In this chapter I revisit the aims and provide an overview of the main findings (Section 5.1); discuss the limitations and lessons of my study (Section 5.2); describe why and how an adaptive management approach should be used (Section 5.3); and provide recommendations for future research and the management and revegetation of landfill sites (Section 5.4).

5.1 Summary of main findings in relation to project objectives

In this section I provide an overview of the research outcomes in relation to each of the aims (Section 1.7).

5.1.1 To provide an overview of research into the revegetation of landfill sites and limiting factors identified

Considering that landfill sites are common globally, there is a remarkable dearth of research that can be used to guide their rehabilitation. The critical need for more research is exacerbated by large variations among landfills in the conditions that are likely to affect rehabilitation. These variations come about through differences in location and climate, size, waste composition, method of filling, type of capping (if any), and characteristics of the final soil layer. Despite variation in all these factors, the literature suggests that some limitations to revegetation are consistent across many landfill sites, e.g., poor planning, use of poor quality soils (low moisture availability, low nutrient levels, saline, low pH or contaminants present), low soil oxygen due to landfill gas and soil compaction, and the presence of a cap preventing deep rooting (see for example, Gilman *et al*., 1979; Gilman *et al*., 1981b; Insley & Carnell, 1982; Ettala *et al*., 1988; Dickinson, 2000). Another factor found to be limiting to the revegetation of landfill sites has been the use of species not suited to the site conditions (e.g., Gilman, *et al*., 1982).

5.1.2 To use the information found, plus local information, to identify potentially limiting factors to vegetation growth on clay capped landfills in Western Sydney

Preliminary examination of my study sites suggested that most of the factors identified in Section 5.1.1; poor planning, use of poor quality soils (low moisture availability, low nutrient levels, saline, generally low pH), low soil oxygen due to compaction, and the presence of a cap preventing deep rooting; could limit revegetation at the Western Sydney landfill sites. Other potential limiting factors included: low and variable rainfall; landforms designed to shed water; and the use of subsoils with the following general characteristics: high bulk density, low pH, low levels of nutrients, especially phosphorus, high salinity, and low in organic content (see Section 2.2).

5.1.3 To develop a list of species that may be suitable for revegetating these landfill sites and to identify limiting factors on the Western Sydney sites

Identifying suitable species was a three-stage process. Firstly, species that met the following basic requirements were identified from the literature and by surveys during site visits: (i) indigenous to the region; (ii) adult plant height of less than 2 metres; (iii) no taproot; (iv) able to grow in heavy clay soils; (v) able to grow in dry conditions; and (vi) rapid growth rate (Section 2.3.1). When compiling this list, the main problem identified was that, for most of the species, there was very limited information available about their germination and growth. The second stage was to identify the subset of these species for which plant material was readily available (Section 2.3.2). This reduced the list of suitable species to 23. The final stage was to produce a list of species that would be used in the trials by revisiting the initial criteria with more emphasis placed upon the species being present at one or more of the experimental sites and known to be potential colonisers after disturbance (Section 2.3.2). These criteria resulted in a list of 17 target species for use in the study.

In order to determine the success of revegetation at the three study sites, germination and planting studies were conducted. For all species, germination rates, seedling survival and plant survival were low between the sites and experimental areas (see Sections 3.2.3, 3.3.3, 4.2.3, 4.3.3). This low success rate was not surprising considering the limiting factors identified.

However, there was high variability both within and between my study sites, with some individual plants, quadrats and areas within quadrats achieving good germination, growth and/or survival results. This high variability illustrates that the limiting factors are variable in presence and/or degree across and between the sites. My study also supported earlier work by Robinson and Handel (2000), who found a weak correlation between the numbers of seeds arriving at patches at an old landfill site and the number of resultant seedlings, the number of seedlings appearing in their patches was also low.

On these clay capped landfill sites, one of the important factors identified as limiting revegetation was the moisture availability in the soil layer. This was an interesting result because the soil layer was a clayey material, and clays have better water retention than courser grained soils (e.g., sandy soils) and the plants used naturally grew in these heavy clays. The limited water availability in the soil was a result of the variable rainfall and non-uniform compaction, resulting in reduced permeability and pore spaces in some areas. In drier climates where surface soil moisture is low, there is usually sufficient water available below the surface, so plants able to root down will be able to survive (Bradshaw & Chadwick, 1980). On landfill sites, however, this is not the case, because rooting depth is limited by the depth of the cap and root growth is limited by the high bulk density of compacted soils. Other limiting factors were herbivory, seed removal, vandalism and ongoing site works. Ongoing site works have been identified as a limiting factor in studies at other landfill sties (e.g., Ettala *et al*., 1988).

5.1.4 To identify the most appropriate method of establishing native plants on these landfill sites

Planting of tube stock and direct seeding were compared in this study to determine whether one of these approaches could be recommended for use in revegetation programs at these sites. However, both methods had very poor overall growth and survival rates. The most successful species in the planting trials was Lomandra longifolia, but it failed to germinate in the direct seeding trials. Several other species, not tested in the planting trial, also failed to germinate in the direct seeding trials (see Sections 3.2.3, 3.3.3 and 4.3.3.1. Other species showed better survival from the direct seeding experiments. For example, *Daviesia*

genistifolia had zero 2 year survival in the planting trial, but, several plants from the direct seeding trial were still alive and healthy 35 months after sowing.

I concluded that both planting and direct seeding may be required if a management objective is to establish a range of species. Direct seeding is much easier, cheaper and quicker, but, a number of species failed to germinate at the sites, so unless the conditions causing this failure can be changed, these species would have to be introduced by planting.

5.1.5 To determine the shape and extent of the root system and the degree to which roots penetrated the cap

Plants from nine species were excavated from three sites both on and off the landfilled area. The root systems of most plants were quite limited and none was found to penetrate into or through the cap. The root systems of plants growing on the landfilled areas were generally small and distorted compared to those from plants growing off the landfills. Many of the plants excavated from the landfilled areas had roots, including taproots, which were deformed and grew either parallel to the surface or even upwards (Section 4.6.3), supporting the findings of Robinson, Handel and others (e.g. Robinson & Handel, 1995; Handel *et al*., 1997).

5.1.6 To discuss the potential of these sites, and clay capped landfills in general, for establishment with native vegetation

Overall the survival and growth of the plants at the three landfill sites examined was very poor. Considering the limitations identified (see Section 5.1.3), this is not surprising, and poor plant survival on landfill sites has been well documented (Gilman *et al*., 1979; Gilman *et al*., 1981a, b; Insley and Carnell, 1982; Ettala *et al*., 1988). Very importantly, however, some plants did survive and grow very well and some areas within the direct seedling trials had good germination and short-term survival rates. High variability between and within sites has also been found by other researchers e.g., Engel and Parotta (2001), Rawlinson *et al*. (2004). There are many factors which may explain the variability in survival observed within landfill sites:

i. Differences in the composition of the cover material, and the way it was placed, e.g., degree of compaction;

ii. Variation in cover thickness;

iii. Presence of landfill gas in the subsoil from minor fissures;

iv. Presence of weed seed;

v. Presence of herbivores.

Some plants produced viable seed during the study period and many flowered. This evidence of reproduction is important for the long-term success of revegetation at the sites. Robinson *et al*. (1992) argued that successful reproduction of planted species, along with recruitment of ecologically desirable species, are important in the successful and economical revegetation of landfill sites. Successful reproduction of the plants on my study sites is particularly important as very little evidence of natural succession was in evidence at two of the sites. In contrast, some researchers found that seed was not only coming onto the landfill sites, but was also resulting in vegetation establishment (Robinson *et al*., 1992; Robinson & Handel, 1993, 2000; Rebele & Lehmann, 2002). The variation in establishment of new vegetation between landfill sites is likely due to the factors already described: soil quality, climate, presence of landfill gas; as well as the presence of a source of seed and appropriate dispersal agents.

From the results of the various trials carried out at these landfill sites and in the laboratory, I conclude that these sites could be successfully revegetated with native species. However, no single technique, species or soil type would be generally suitable and it is still difficult, even after this study, to predict which species could be established readily under particular conditions. Adaptive management is the only effective approach to dealing with this sort of situation.

5.2 Limitations and lessons

The challenges of conducting some of my studies revealed a number of issues that need to be considered in future work. Some of these highlight problems that could be avoided, and others suggest unexpected processes or interpretation of patterns.

i. Herbivores

This research did not effectively test the importance of herbivory, though this was revealed as a potentially significant factor limiting rehabilitation. I set up two experiments to examine the impact of mammalian herbivores on plant growth and survival; but poor survival rates, damage to site fencing and interference from vandals, prevented statistical comparison of treatments (see Sections 3.4, 4.5). These experiments did, however, highlight the importance of good site fencing in managing site rehabilitation, and the overriding impact of the weather. In the second herbivory experiment, low rainfall had a greater impact on plant survival than herbivory or vandalism (see Section 4.5).

ii. Importance of the weather

Lack of rainfall during much of the experimental period limited both plant survival and growth (see Sections 3.2, 4.2 and 4.5). This highlights the importance to managers of being prepared to deal with a range of different climatic conditions during site rehabilitation. My results might have been substantially different if they had been conducted during a period with more regular and substantial rainfall.

iii. The variabilities of fieldwork

By its very nature, conditions in the field vary greatly in space, at a variety of scales. Although each of the landfill sites studied was in the same geographical area, was managed by the same company, following the same guidelines, and capped with heavy clays from the surrounding area, the sites still experienced different climate, landscape and soil type. Factors that obviously varied within my study sites included soil type, rockiness, surface roughness, slope, aspect, and microclimate. While variation of this nature is typically dealt with by replication of sites and study plots within sites, at two of the experimental sites there was high variability even within some of the 1 m^2 quadrats. Variation at this scale was not anticipated. A search of the literature failed to identify other research which had described high variability within such small areas.

iv. Plant material used in experiments

Individual plant survival is typically due to the combined effects of genotype and site conditions. This is an important point often overlooked with research into rehabilitation.

Sufficient replication would make it possible to identify the importance of environmental conditions despite the variation in growth and survival that might be attributable to genotype. However, where survival rates are as low as I found in this research, it is possible that different performance of individual genotypes explained differences between treatments. This could be addressed, even with low numbers, by comparing plants grown from cuttings or tissue culture.

v. Changing landfill management regime

When the research began, Site 2 and several areas of Site 3 were actively being landfilled, and were not available for trials. Site 1 was not available for the field experiment using mulch and water treatments to increase soil moisture, due to a change in management over the time-span of my study. These are the realities of research on actively managed sites, especially where the research is conducted over a number of years.

5.3 An adaptive management approach

Whilst many of the findings of this research relate to landfill sites in general, it is important to recognise that sites and species vary, so landfill sites cannot necessarily be treated and managed in the same way. Variation in the factors limiting plant growth at particular sites, variation in the species that are available and suitable for growing on landfills, and variation in how plant roots interact with the cap, all indicate that an adaptive management approach will be needed in landfill rehabilitation – it is unlikely that a formula-based approach could be established that might apply in many situations.

The results yielded from the experiments at these sites in Western Sydney well illustrate the need for adaptive management. Adaptive management is a flexible and changing management system with the following outline: a clear purpose, development and implementation of a plan and related monitoring system, analysis of results, and use the results to adapt the plan (Johnson, 1999).

An adaptive management approach requires time, observation and the ability to change, but it allows active management to be applied without delay. A landfill management plan can incorporate adaptive management by including the testing of different treatments, a clear well targeted monitoring program, the results and observations then incorporated into future management actions. For example, if a planted species exhibits poor growth and survival, the suitability of the species, the planting technique and source of material, can be examined to identify and rectify the problem prior to further planting. Thus, it is essential that a landfill management plan be a work in progress that is regularly reviewed and updated, i.e., is adaptable.

An adaptive management approach could be well utilised at the three sites examined in this study. Limited available soil water was identified as a limiting factor, and watering would be difficult due to inconsistent availability of supply and the frequent presence of vandals. Methods of breaking the soil compaction and incorporating organic matter would be well worth trying in targeted areas, with monitoring to determine success. Planting around the landfilled area in lower lying areas and adjacent to ponds would be valuable in getting some of the target species established on the site. These plants would then be a source of seed for future regeneration at the sites: this has been identified as an important factor in the long-term revegetation of degraded sites (e.g., Robinson & Handel, 2000). Mammalian herbivory was identified as a limiting factor at two of the sites; at Site 1 the herbivores came from an adjacent property in which case communication and working with the neighbours may prove valuable. At Site 2 goats were found to have been fenced onto the site, it should be determined how, and by whom, these animals can be removed. Tree guards seemed to be effective against the hares that were present at each of the sites when not damaged by larger herbivores or vandals; the plan should now include the use of guards with all new plantings.

A perfect adaptive management model is unlikely to be completely successful at these sites as the organizations legislating and the companies managing them are not completely flexible and there is no clear long-term plan. Part of the limited flexibility can come about from personnel with limited knowledge of revegetation, but, being required to make choices and undertake related work (see Section 1.4.1). This lack of flexibility has been described as a common problem in adaptive management (Johnson, 1999). However, while limited flexibility may

reduce some options, the principles of adaptive management still have a lot to offer in terms of the focus on planning, well-targeted monitoring, and putting into practice the results of the monitoring. Apart from limited knowledge, uncertainty is also prevalent in the lack of long-term planning. However, many researchers have argued that adaptive management can be used with uncertainty and indeed, that uncertainty is unavoidable (e.g., Gilmour *et al*., 1999; Costello *et al*., 2000).

5.4 Recommendations

A number of recommendations, based on the findings of this research, are presented as a guide to those who are undertaking research into landfill management, or are responsible for managing landfill sites specifically and undertaking revegetation in general.

5.4.1 Recommendations to landfill and degraded land researchers

It has already been noted that there is a dearth into the revegetation of landfill sites, compounded by the high variability between sites. The good news is that there are lots of areas where research can play an important part in landfill management and research into on many different questions will yield important information. In this section, several research questions are outlined which would be particularly valuable in the understanding and management of landfill sites.

What level of soil moisture is required to both allow germination and maximise survival rates for different species in different soil conditions? This is a complex question and cannot be answered by a single experiment. Simply more knowledge and understanding of how different species grow in different conditions is required. While undertaking my study one of the limiting factors identified was a lack of knowledge about the species, their growing requirements and response to different conditions. All research into different plant species and how they respond to different conditions is valuable.

With the poor germination and survival rates observed, one of the questions raised was how much of the survival may be related to genotype rather than variation in the limiting factors at the sites. Research is required comparing the success of plants grown from seeds and cuttings with plants sourced from near the study sites on similar soils and those from further away on different soils. Bradshaw (1952) argued that genotype can be an important factor in the revegetation of degraded sites. While this argument and need for related research has been around for a long time, little research has been conducted relating to landfill sites.

The removal of seeds was found to be a very interesting factor in the possible limitation to revegetation at these sites. Further work on seed removal and, the fate of these seeds would be invaluable. Seeds from particular species were moved from the caches by ants at higher rates than other species, it is important to know if the ants are eating or otherwise damaging these seeds so that germination is not possible. Some research has been undertaken on the fate of seeds in other areas; the results have been varied with some seeds being consumed (e.g., Handel & Beattie, 1990), while many Australian species are myrmecochorous and so require ants for dispersal (e.g., Berg, 1975).

5.4.2 Recommendations to the managers of landfill sites

The most important issue in the revegetation of landfill sites, and other sites, is planning. Consenting bodies in Australia and many other countries today require detailed plans to be developed at the start of a landfilling project. It is not enough to have a plan - it needs to be taken into consideration throughout all of the landfilling operations. It is recommended that managers undertake revegetation work throughout the lifetime of the landfill project and not wait until after landfilling is complete. This is particularly valuable where there are large differences in annual rainfall and where indigenous species will be used, as many native plant species are not available commercially. The landfill management plan also needs to be flexible and updated to allow for new knowledge and the results of monitoring at the site to be taken in to consideration.

Ideally, the best time of year to undertake revegetation work would be identified and the final cover would be complete at that time; however, it is impractical to specify exactly when

landfilling would cease, capping completed and the final cover deposited. Additionally, identifying the best time of year is not simple either; for example, it may be dependent on when the rains arrive and may vary between species.

It is recommended that personnel be stationed at the site after landfilling activities are complete to monitor and maintain vegetation. It may not be practical to water and maintain a whole site with many hectares, but, if the surrounding areas have been revegetated during the landfilling there is a buffer zone and a source of seed. If adverse weather conditions occur, such as very low rainfall at the time of sowing and/or planting, and it is not practical/possible to water the whole site, focus on patches. If patches of vegetation can be established on the landfill surface, they will provide protection for an area from erosion, and will be a source of plant material for when conditions improve.

5.4.3 Recommendations to the legislative requirements of landfills

There is a tendency among some regulatory bodies to require landscape architecture style plans for the revegetation of all sites. This can include the neat and exact placement of plants, along with a precise species list. Where plants are being grown for the site from locally sourced material, much can go wrong (e.g., insect damage to seeds prior to harvesting). If that species is not used, the conditions set in the development approval will not then have been met. It is recommended that legislation and regulation be designed in such a way as to allow managers broader scope so that site conditions may be taken into consideration. For example, rather that prescribing species, or even requiring managers to provide an exact list of plants and where they will be planted, planting areas should be identified along with a minimum number of plants from a specified list of species to be used. This provides the regulatory body with sufficient assurance, and provides scope for the managers on the ground to work out the best possible solution for the individual site.

The same general comment holds for requirements for the soil cover. Rather than prescribing the physical and chemical characteristics of the soil cover with very strict and precise guidelines about what is required (which is an increasing trend in the USA), managers of landfill sites could be required to operate within the general characteristics of the soil material

and provide justification for using a particular type of soil (or range of soil types). This would allow soil cover to be tailored to the conditions of a particular site and would minimise the necessity to strip topsoil from other areas.

Each of these points relates back to the need for adaptive management. There is no one way of managing a site. The individual needs of the site relating to its location, surrounding land use, onsite conditions, future use, and results of onsite monitoring all need to be taken into consideration when a landfill management plan is developed. A system also needs to be in place whereby an approved plan can be altered to take into consideration new knowledge, changes to the site conditions and the results of monitoring.

5.4.4 Recommendations to managers of land to be revegetated

Revegetation work takes a good deal of time, and can be expensive, especially if particular seed and/or plant material is to be collected and/or propagated. Detailed planning is therefore required well in advance of rehabilitation. This planning needs to include: an assessment of the information already known about the site; the availability, or otherwise of detailed vegetation maps of the area and the site; the presence, absence and quality of remnant vegetation; and the availability of personnel who have sufficient expertise in plants and revegetation.

Given the variability in plant responses and the lack of knowledge about particular indigenous species, adaptive management could start with experimental rehabilitation in areas around the landfill and adjacent to buildings and equipment storage, at a very early stage, even while the landfill is active. A review of these trials then allows modification of the larger plan for the landfill proper.

Fencing is certainly effective at keeping our certain large herbivores, e.g., cattle and horses. It is important, however, that the fencing be maintained and that the animals in question are not fenced within the area of rehabilitation!

Many unanswered questions remain and others have been posed as a result of this research. When doing rehabilitation work, there are many factors which can influence both the short and long term success. It is essential that information from revegetation trials is pooled, so that we may develop a better understanding of the potential limiting factors in a range of environments and conditions using a range of species. It is all too easy to say that something was tried and it did not work and not do it again. This is a reasonable supposition if all of the factors are the same, but in revegetation programs this is rarely likely to occur. To make revegetation at challenging sites successful, we need to plan, to be flexible, to experiment and to adapt.

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Appendix A

Soil results

Table A Soil sample results for Sites 1, 2 and 3

	pH		Phosphorus	Ammonium	Nitrate	Sulfate	Salinity	Chloride	ECEC					
									Sodium	Potassium	Calcium	Magnesium	Aluminium	Total
	1:2 in water	1:2 in $CaCl_2$	Bray No. 1 acid fluorite extract	1:2 in 0.01 M $CaCl_2$	1:2 in water	1:2 in water	1:2 in water conductivity	1:2 in water	NH_4Cl 1 mol/L pH 6.0					
Sample			mg/kg DL 0.8	mg/kg	mg/kg	mg/kg	mS/cm	mg/kg	cmol/kg	cmol/kg	cmol/kg DL 0.2	cmol/kg	cmol/kg	cmol/kg
Site 1*														
1	4.8	4.1	BDL	28.6	0.5	102	0.7	302	1.91	0.22	1.70	6.49	1.77	12.09
2	5.2	4.7	BDL	14.6	0.5	92	1.0	390	2.68	0.17	6.39	6.76	0.57	16.57
3	4.5	4.1	BDL	22.1	0.5	160	1.8	1022	4.08	0.26	1.13	7.12	1.50	14.09
4	4.5	4.1	BDL	19.6	0.5	140	1.5	805	2.32	0.29	1.83	7.03	1.85	13.32
5	4.7	4.1	BDL	19.9	0.5	127	1.2	609	2.40	0.24	1.93	7.05	1.71	12.79
Site 2*														
1	5.4	4.2	1.1	22.1	14.7	67	0.3	-	1.01	0.17	0.61	5.73	2.31	9.83
2	7.1	6.2	BDL	16.5	6.4	113	1.0	353	1.92	0.23	3.34	6.63	-	12.12
3	7.3	6.9	BDL	15.7	0.5	204	2.5	1169	2.95	0.25	2.14	6.54	-	11.88
4	8.6	8.0	BDL	15.1	5.5	60	1.2	392	2.46	0.18	2.74	6.82	-	12.20
5	4.9	4.3	BDL	9.0	0.9	138	1.3	686	2.17	2.30	5.30	67.80	6.80	12.19
6	6.4	6.0	7.6	8.7	0.9	144	2.7	1533	2.70	0.21	0.94	7.42	-	11.27
7	6.9	6.7	BDL	18.8	4.1	68	2.3	1736	2.96	0.22	1.1	10.82	-	15.10
Site 3*														
1	5.4	4.7	BDL	14.8	4.1	38	0.6	-	0.62	0.12	0.20	2.98	0.03	3.95
2	6.2	5.1	BDL	11.5	2.8	102	0.2	-	3.95	0.11	-	8.03	-	12.09
3	6.5	5.9	BDL	11.8	4.6	30	0.3	-	3.85	0.07	0.13	7.41	-	11.46
4	6.4	5.6	BDL	14.8	4.1	35	0.3	-	4.08	0.08	0.03	7.37	-	11.56
5	6.3	5.9	BDL	5.3	BDL	372	2.1	1036	2.96	0.20	1.45	9.89	-	14.50
6	5.6	5.2	BDL	4.2	BDL	85	2.1	1673	2.58	0.18	BDL	10.42	-	13.35
7	5.9	5.6	BDL	15.4	BDL	140	2.1	1260	4.12	0.15	BDL	14.45	-	18.86

* Site 1 – each of the 5 samples was collected from the planting area with the corresponding number; Site 2 – each sample was collected from stockpiled material used to cover the landfilled area; Site 3 – samples 1 and 2 were collected from revegetation area 1, samples 3 and 4 were collected from revegetation area 2 and samples 5, 6 and 7 were collected from other areas on site covered with soil material from onsite.

Appendix B

Field recording sheets

B1: Field recording sheet for 10 quadrat germination study at Site 2

Direct Seeding Trial - Sown -16 May 1996, Site 2											
100 seeds per species in 1m2 plots, except for the Melaleuca											
	Date	1a	1b	2a	2b	3a	3b	4a	4b	5a	5b
		TL	TR	FL	FR	RF	RB	BL	BR	LF	LB
Acacia linifolia											
Acacia ulicifolia											
Atriplex semibaccata											
Bursaria spinosa											
Dillwynia juniperina											
Daviesia ulicifolia											
Hardenbergia violacea											
Kennedia rubicunda											
Indigofera australis											
Lomandra longifolia											
Melaleuca thymifolia											
TOTAL											

B2: Field recording sheet for planting experiment at Sites 1 and 2

Example sheet for Site 1 Planting area 1

DATE	Plant #	HEIGHT	WIDTH	GRAZE	HEALTH	OTHER	Plant #	HEIGHT	WIDTH	GRAZE	HEALTH	OTHER
SITE	SPECIES						SPECIES					
PLOT	000						000					
	001						001					
SAMPLING	002						002					
	003						003					
GENERAL COMMENTS	004						004					
	005						005					
	006						006					
	007						007					
	008						008					
	009						009					
	010						010					
	011						011					
	012						012					
	013						013					
	014						014					
	015						015					
	016						016					
	017						017					
	018						018					
	019						019					
	020						020					

Plant #	HEIGHT	WIDTH	GRAZE	HEALT	OTHER
SPECIES					
000					
001					
002					
003					
004					
005					
006					
007					
008					
009					
010					
011					
012					
013					
014					
015					
016					
017					
018					
019					
020					

SPECIES	SPECIES	SPECIES
000	000	000
001	001	001
002	002	002
003	003	003
004	004	004
005	005	005
006	006	006
007	007	007
008	008	008
009	009	009
010	010	010
011	011	011
012	012	012
013	013	013
014	014	014
015	015	015
016	016	016
017	017	017
018	018	018
019	019	019
020	020	020

SPECIES	SPECIES	SPECIES
000	000	000
001	001	001
002	002	002
003	003	003
004	004	004
005	005	005
006	006	006
007	007	007
008	008	008
009	009	009
010	010	010
011	011	011
012	012	012
013	013	013
014	014	014
015	015	015
016	016	016
017	017	017
018	018	018
019	019	019
020	020	020

B3: Field recording sheet for mulching and watering experiment at Sites 2 and 3

Example sheet for Site 2

Site: Site 2 (Schofields)														Plots read from front to back and left to right						
Date																				
	Comments																			
	Plot 1 (TL)				Plot 2 (TR)				Plot 3 (FL)				Plot 4 (FR)				Plot 5 (LF)			
Species	Water	W&M	Mulch	None	Water	W&M	None	Mulch	W&M	Water	Mulch	None	None	Mulch	W&M	Water	Water	None	Mulch	W&M
As																				
Al																				
Bs																				
Cc																				
Dg																				
Du																				
Hv																				
Ia																				
Kr																				
Ll																				
Mt																				
Od																				
Unknown																				
Total																				
Comment																				
	Plot 6 (LB)				Plot 7 (BL)				Plot 8 (BR)				Plot 9 (RB)				Plot 10 (RF)			
Species	W&M	Water	Mulch	None	W&M	Water	None	Mulch	Mulch	W&M	Water	None	None	W&M	Mulch	Water	W&M	Mulch	Water	None
As																				
Al																				
Bs																				
Cc																				
Dg																				
Du																				
Hv																				
Ia																				
Kr																				
Ll																				
Mt																				
Od																				
Unknown																				
Total																				
Comment																				

B4: Field recording sheet for plant removal experiment at Sites 1, 2 and 3

GENERAL INFORMATION				
Site			Species	
Date			*Plant label*	
Sampler		Time started		Time completed
LOCATION DESCRIPTION				
Location				
Slope			Aspect	
Photographs - Initial:		After weeding:		With roots exposed:
Mulch present Y / N		If yes, depth (mm)		Type
PLANT DESCRIPTION				
Plant type				
Height	*Width*	*Graze*	*Health*	*Other*
ROOT SYSTEM				
General description of roots				
Lateral spread (general)				
Depth (general)				
Tap root present Y / N		If yes, depth		& shape
Max root diameter (mm)				
Are roots even around the half exposed Y / N			If no, comment	
Shape/Spread of root system				
White fungal mass present on roots Y / N			If yes, sample	
Nodules present on roots Y / N			If yes, sample	
Comments				
Root samples			Soil samples	
Depth from root base to waste (landfill samples only)				
Other				