THE ECOLOGY AND INTEGRATED MANAGEMENT OF BROOM (*Cytisus scoparius*) IN NEW ZEALAND PLANTATION FORESTS

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Abstract

Broom (*Cytisus scoparius*) is a major weed of radiata pine (*Pinus radiata*) plantations in New Zealand. The objective of this work was to determine how best to discourage broom establishing successfully within newly planted pine forests. Measurements of seed banks under pine forests showed that broom seeds can accumulate in the soil prior to the trees being harvested, with over 3500 seeds m^{-2} of high viability being found in some forest soils. Seeds germinate immediately once scarified, but unscarified seeds break dormancy over time, and temperature fluctuations within bare soil are thought to help break seed coats. A field trial in which several different grass species were sown at different rates showed that grasses establishing at the same time as broom seedlings have little detrimental effect on broom establishment, regardless of whether planted in spring or autumn. However, if grasses had been established for six months prior to broom seeds germinating, no broom survived. A range of herbicides were tested for their ability to control broom from three months to 12 months in age. Most herbicides tested gave good control of broom seedlings, including hexazinone, terbuthylazine, and several combinations of clopyralid, triclopyr and picloram, though some herbicides were better than others on older plants. Herbicides were also assessed to determine how persistent they are within soil for controlling broom seedlings that begin establishing several months after a herbicide was applied. Three of the most persistent treatments were hexazinone, clopyralid and a triclopyr/picloram mixture. A range of herbicide and ground cover treatments were assessed in a newly planted pine forest in Hawkes Bay for their effect on broom establishment. The most effective strategy for discouraging broom problems in pine forests is thought to involve planting grass ground covers then using a herbicide mixture based on clopyralid with some picloram and triclopyr added to selectively remove broom from among young pines and the grass sward within the first 12 months. Following this herbicide application, subsequent establishment of further broom seedlings should be prevented initially by residues from the herbicide then later by the grass sward.

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CHAPTER 1
GENERAL INTRODUCTION

1.1 Introduction

One of the main threats to biodiversity worldwide is the direct destruction of habitats by people, mixed with climate disruption as a consequence of inappropriate uses of resources or pollution (Cronk *et al.* 1995). The next serious danger, though underestimated, is the invasion of alien organisms to the natural and semi-natural habitats, such invasions can be a lasting and pervasive threat (Coblentz 1990). It is a lasting threat because when the exploitation or pollution stops, ecosystems often begin to recover. However, when the introduction of alien organisms stops, the existing aliens do not disappear and sometimes continue to spread and consolidate, becoming more pervasive (Cronk *et al.* 1995).

Among the many threats to ecosystems, invasive plants are becoming seen as being increasingly important as awareness by conservationists and managers increases. Several definitions of invasive plants have been used, of which the most simple is a plant that enters a territory in which it has never occurred before regardless of circumstances. Another definition which states an invasive plant as a species capable of establishing self-sustaining populations in areas of natural or semi-natural vegetation (Macdonald *et al.* 1989). An invasive plant is defined as '*an alien plant spreading naturally (without the direct assistance of people) in natural or semi-natural habitats, to produce a significant change in terms of composition, structure or ecosystem processes*' (Cronk *et al.* 1995).

Three closely related but not identical concepts (weeds, colonizers and invaders) have been suggested (Rejmánek 1995), of which the former is of our primary concern as "*plants (not necessarily alien) that grow in sites where they are not wanted and which usually have detectable economic or environmental effects by suppressing and/or limiting the productivity of desired plants*" (Rejmánek 1995; Randall 1997; Richardson *et al.* 2000).

Broom (*Cytisus scoparius* (L.) Link), which had been naturalised in New Zealand since 1872 (Owen 1998), was utilised as stock food (Williams & Cameron 2006) and has recently become a valuable source of pollen for bee-rearing activities (Hannan 1998; Jarvis *et al.* 2006). However, broom is generally unwanted by farmers, forest owners and conservationists because it reduces carrying capacity on farms, increases forest establishment and tending costs (Syrett *et al.* 1999), invades braided riverbeds, destroys breeding sites of endemic wrybills (*Anarhynchus frontalis* Quoy and Gaimard) and black stilts (*Himantopus novazealandiae* Gould), and harbours their introduced predators (Owen 1998).

In New Zealand, radiata pine (*Pinus radiata* D. Don) is an important forest species, occupying 1.6 million ha throughout the country (Watt *et al.* 2003c; Watt *et al.* 2007). Besides being a weed of pasture and natural ecosystems, broom is a major weed of forestry (especially *P. radiata*) plantations (Syrett *et al.* 1999; Watt *et al.* 2003b). The competition of broom plants on young pine trees for light, water and nutrients has been reported (Richardson 1993; Watt *et al.* 2003b). Broom seedlings that regenerate from the seed bank following clear-felling can impact plantation growth over a 5–6 year time frame before becoming overtopped and eventually shaded out by canopy closure (Richardson 1993; Paynter *et al.* 2012). Some management regimes using various control methods have been applied to control vegetation, including broom, in New Zealand forests (see Richardson (1993) for details). However, the broom biological control program has made slow progress in New Zealand (Fowler *et al.* 2000) and further understanding of broom ecology is necessary for finding more suitable control approaches.

The long-lasting impacts of broom on *P. radiata* during the first couple of years of plantation establishment have been of concern to forest management in New Zealand and worldwide. This thesis aims to find suitable management schemes to reduce the invasion of broom at early stage of *P. radiata* establishment, where broom is more competitive with young pine seedlings. The next section of this chapter reviews some of the aspects of broom ecology and management. The final section summarises research objectives.

1.2 Literature reviews

Broom (*Cytisus scoparius* (L.) Link) is a European leguminous shrub (Downey 2002) and has become a vigorous invader of temperate plant communities worldwide (Holm *et al.* 1997). Broom has become an interesting species for many theoretical and practical studies due to its paramount importance as an invasive weed to many areas, including agricultural, forestry and conservation lands especially outside its native range (Syrett *et al.* 1999). It was accidentally or intentionally introduced inNew Zealand and is the only broom species that is a noxious weed, invading open grasslands on both productive and conservation lands (Syrett *et al.* 1999). It can compete vigorously with newly-planted conifer seedlings (Watt *et al.* 2003a) and thus causes production losses in forestry as well as in agriculture. In natural areas, it reduces conservation values (Syrett 1996). This section reviews some aspects of ecology of broom and management and control strategies.

1.2.1 Taxonomy

Family: Fabaceae
Subfamily: Faboideae
Tribe: Genisteae
Genus: *Cytisus*
Species: *scoparius* (L.) Link
Synonymous scientific names: *Sarothamnus scoparius* Koch and *Spartium scoparius* (after Bossard *et al.* (2000))
Common names: broom, Scotch broom, Scot's broom, Scottish broom, English broom and common broom.

Other similar genera in this family are *Genista* with Montpellier broom also known as French broom or Cape broom (*Genista monspessulana* syn. *Cytisus monspessulanus* or *Teline monspessulana*) and Mediterranean broom (*Genista linifolia*). Spanish broom (*Spartium junceum* syn. *Genista juncea*) is the sole species in the genus *Spartium,* but is closely related to the other brooms in the genera *Cytisus* and *Genista*.

1.2.2 Invasion history of broom in New Zealand

Like gorse (*Ulex europaeus* L.), broom was introduced by European settlers and was naturalised in New Zealand by 1872 (Owen 1998). It was utilised as stock food (Williams & Cameron 2006) and has become a valuable source of pollen for bee-rearing activities (Jarvis *et al.* 2006). Initially less invasive than gorse, primarily because of its palatability to stock, broom is now spreading rapidly in both main islands (Williams & Cameron 2006). Broom is unwanted by farmers, forest owners and conservationists because it competes with forage species, increases the costs of forest establishment and tending (Syrett *et al.* 1999), invades braided riverbeds and destroys breeding sites of endemic wrybills (*Anarhynchus frontalis* Quoy and Gaimard) and black stilts (*Himantopus novazealandiae* Gould), and harbours their introduced predators (Owen 1998).

1.2.3 Description

Broom has unarmed ascendent five-angled stems (Hosking *et al.* 1996) that are green and hairy, and later become glabrous and woody when the plant matures (Peterson & Prasad 1998; Bossard *et al.* 2000) and the ratio of woody to green tissue changes (Waloff & Richard 1977). Leaves are generally trifoliote, alternating around five-angle sides (Downey 2002). Broom can form dense stands in cooler areas but their leaves are shed in winter in colder areas and in summer in regions that experience drought (Hosking *et al.* 1996; Peterson & Prasad 1998).

Juvenile broom plants can endure a broad range of light conditions and accordingly a wide range of growth habitat (Williams 1981). Broom tolerates strongly acid soils and those with very low levels of native inorganic phosphorus, but can respond readily to higher levels of native phosphorus or added superphosphate. Broom therefore is able to adapt to a wide range of phosphorus conditions in New Zealand.

1.2.4 Distribution and uses of broom

Broom has a wide distribution in Europe, ranging from southern Scandinavia to the Azores and from Europe's Atlantic coast to Hungary and Ukraine (Smith 2000) with a range of temperate and Mediterranean climatic zones. It has been introduced into many temperate regions including Australia, eastern and western Canada, Chile, India, Iran, Japan, New Zealand, South Africa and eastern and western USA (Holm *et al.* 1979;

Fowler *et al.* 1996; DeLoach 1997; Syrett *et al.* 1999), where it has invaded and become established in a wide range of habitats, such as agricultural areas, grasslands, forests and conservation lands (Williams 1981; Wheeler *et al.* 1987; Hosking *et al.* 1996; Watt *et al.* 2003a). Potter *et al.* (2009) determined the worldwide distribution of broom (Fig. 1.1) using both data obtained from a literature review and a survey of locality data held by various institutions and used this information along with the CLIMEX model to infer the climatic conditions of broom from its native range and exotic ranges. Rejmánek and Richardson (2013) noted that broom has become an important invasive weed in eight regions (North America, Asia, New Zealand, Australia, Africa (southern), Atlantic islands, South America and Pacific islands) among others.

Figure 1.1. Worldwide distribution of broom (adapted from Potter *et al.* (2009)). Grey shading indicates the native distribution of the weed, cross hatch indicates administrative units where broom has been recorded and triangles indicate historical point locations where broom has been recorded.

In France, broom has been used in traditional farming systems and used to restore soil fertility and to produce fuelwood for bakeries (Prévosto *et al.* 2004; Prévosto *et al.* 2006). In Spain, due to its ability to grow in contaminated mining areas with high biomass and potential resistance to arsenic, broom has become a good candidate to revegetate arsenic-contaminated sites (Manzano *et al.* 2012). In Japan, broom has been used for post-fire erosion prevention (Nemoto *et al.* 1993; Smith 2000). In North America, broom was introduced as an ornamental and then used to prevent soil erosion and stabilise coastal dunes in USA (Bossard 1991) and to stabilise highway embankments and land rehabilitation in Canada (Peterson & Prasad 1998). In Australia, broom has become a serious weed and infestations cover ca. 10,000 ha at Barrington Tops, and has become a threat to the Australian alps national parks (see Hosking *et al.* (1996)). Broom is capable of forming dense and mono-specific stands over large tracts of land in New Zealand (Parsons & Cuthbertson 1992), abandoned pastures in France (Prévosto *et al.* 2004) and the USA and elsewhere (Syrett *et al.* 1999).

1.2.5 Habitat

Climatic requirements

Broom appears at elevations ranging from the sea level to approximately 1000 m in temperate zones and over 1000 m in warmer regions such as Australia and New Zealand (Peterson & Prasad 1998). In North America, the distribution of broom is restricted in the north and inland by cold winter temperatures (Peterson & Prasad 1998). In Australia broom occurs mainly in cool temperate areas (Hosking *et al.* 1996).

Broom and soil conditions

Broom is usually a calcifuge in its native range (Hosking *et al.* 1996), but outside its indigenous area it seems to be well-adapted to various soil types. In New Zealand, broom is well adapted to a wide range of soils and parent materials but grows especially rapidly on fresh alluvium and recent soils with a high level of inorganic phosphorus. Broom can be seen in both low and high elevation sites but its growth is faster at low elevations on moderately fertile soils (Williams 1981). In Australia, broom is found on soils originated from a series of substrata, especially basalt, growing well on humid, fertile soils and even on undisturbed sandy soils (Hosking *et al.* 1996). In Canada, broom can survive on a range of soils such as brunisols, podzols and regosols but prefers nitrogen-medium soils and flourishes on disturbed, well-drained sites but does not do well on calcareous soils (Peterson & Prasad 1998).

Plant associations and impacts of broom on soil conditions and invaded vegetation

Broom is associated with grasslands, woodlands, open forests (Hosking *et al.* 1996) and open areas (Prévosto *et al.* 2006). Its seedlings can grow vigorously and soon form dense stands, replacing native plant species and altering community structure of prairies, old-fields, woodlands and newly-established forests (Bossard & Rejmánek 1994; Diquélou & Rozé 1999; Wearne & Morgan 2004; Blair & Zedaker 2005; Srinivasan *et al.* 2007) and altering the functioning of these ecosystems by modifying the environmental variables: light and soil moisture regimes and nitrogen dynamics (Diquélou & Rozé 1999). It is distributed along highways and power lines, right-of-ways and meadows (Peterson & Prasad 1998). Broom is subsequently found to establish after soil or vegetation disturbance such as fire, herbicide treatment (Hosking *et al.* 1996), logging, grazing abandonment (Fogarty & Facelli 1999) and other causes (Peterson & Prasad 1998).

In France, mature broom stands (100% broom cover) were estimated to reduce 89% of the incident light from reaching ground level and that prevented further invasion of broom seedlings and increased water availability compared with those of other intermediate stands (78% broom cover) or without broom colonisation (Prévosto *et al.* 2006). Moreover, soil fertility showed the same trend with C and N contents, where they increased in the upper layer from the grazed pasture to mature broom stands (Prévosto *et al.* 2006). In another study in temperate forests of France, the growth of *Picea abies* stands was markedly decreased by dense cover of broom plants with the incident light intercepted by more than 90% by the mature and dense broom canopies (Gaudio *et al.* 2008).

In North America, broom prevents the successful regeneration of Douglas-fir (*Pseudotsuga menziesii* (Merbel) Franco) (Isaacson 2000) and is associated with other shrubs such as arbutus (*Arbutus menzeisii* Pursh), gorse (*U. europaeus* L.) and Himalayan blackberry (*Rubus armeniacus* Focke) in British Colombia, Oregon and Washington (Peterson & Prasad 1998), and *Pinus ponderosa* Dougl. ex Laws. in California (Bossard 1991). Broom has invaded well-drained sites in the Pacific

Northwest and reduced the economic value of pasture through its competition with pasture forage species and seedlings of conifers (Syrett *et al.* 1999). As well as directly competing with other vegetation, broom also appears to have ecosystem effects on soil nutrient status. In a Pacific coastal prairie, Caldwell (2006) found levels of inorganic phosphorus under broom-invaded soils were lower than those of adjacent non-broom-associated soils. Shaben and Myers (2010) also recognised the same trend with soils sampled in an intact fragment of Garry oak savannah in Rocky Point, British Columbia. Grove *et al.* (2012) found that broom-invaded soils reduced Douglas-fir growth compared to uninvaded forest soils and that allelopathy plays a critical role in the reduced effect of broom.

In India, Srinivasan *et al.* (2007) found that the species richness and biomass of native plants did not clearly decline with increasing broom densities. Although the species diversity values were not very different between broom stands and grassland plots, the composition of native plants differed in patterns of dominance, suggestive of species replacement rather than loss.

In Australia, broom has infested *Eucalyptus* spp. forests in New South Wales, Victoria and South Australia, caused a serious hazard to some national parks and grazing land and to some commercial forests in Tasmania (Hosking *et al.* 1998; Syrett *et al.* 1999) and changed the community structure and soil seed bank of subalpine vegetation (Wearne & Morgan 2004; Wearne & Morgan 2006). The results obtained by Wearne and Morgan (2004) showed that the appearance of broom has substantially changed floristic composition and species richness after 15 years and became more evident after 25 years due to dense canopy shading and homogenous litter layer in the understory.

In New Zealand, broom is pervasive and plentiful in the more arid eastern areas and invades open grasslands on both productive and conservation lands (Syrett *et al.* 1999) and forestry plantations by competing vigorously with newly-planted conifer seedlings (Richardson *et al.* 1993; Richardson *et al.* 1996b; Watt *et al.* 2003b). It has also been blamed for reducing economic and conservation value on agricultural and forestry lands (Syrett 1996). Moreover, broom is capable of rapidly forming dense and mono-specific stands, overtopping and then replacing the vegetation of natural or semi-natural ecosystems (Prévosto *et al.* 2006). In the eastern montane grassland of New Zealand, broom invades the native nitrogen-fixing shrubland dominated by matagouri (*Discaria toumatou*) and short tussock species and is maintained by periodic burning (Bellingham 1998).

Broom could also become a widespread and damaging invader in South Africa. Naturalising roadside populations in the foothills of the KwaZulu-Natal Drakensberg were repeatedly cleared in the 1980s by digging them out, but in the early 1990s the plants were seen to be re-growing from the roots leading to the use of a foliar herbicide treatment (Mkhize *et al.* 2013).

1.2.6 Growth and development

Morphology and physiology

Broom has special morphological traits with a remarkable reduction in leaf surface and green photosynthetic tissues located in the stems (Williams 1981; Bossard & Rejmánek 1992) as well as the leaves (Hosking *et al.* 1996). Stem photosynthesis has been estimated to account for approximately 40% of photosynthates produced overall which increases tolerance to leaf herbivory (Bossard & Rejmánek 1992) and the constant carbon gain throughout the year, from stem assimilation, may enhance the growth capacity of broom in disturbed habitats (Nilsen *et al.* 1993).

Broom is shade-intolerant and its seedlings usually die if germination occurs beneath mother trees and other thick canopies (Hosking *et al.* 1996). However, there are several features of its life-history that make broom well suited to invading open and exposed areas (Allen & Allen 1981; Peterson & Prasad 1998):

- The deep rooting habit with the ability to fix nitrogen (Allen & Allen 1981), albeit relatively poorly (about 111 kg N ha^{-1} $year^{-1}$) (Watt *et al.* 2003a) compared to other agricultural legumes (Wheeler *et al.* 1979).
- The early and massive seed production (Paynter *et al.* 2000) and a long-lasting seed bank (see Prévosto *et al.* (2006)).
- The rapid development of roots and foliage, and an ability to resprout after exposure to disturbances.

Broom's fast start and high relative growth rate, high competitiveness in nutrient-rich soils and its ability to change nutrient availability could be important contributors to the mechanisms by which it invades native woodlands.

In New Zealand, broom has a wide tolerance of soil conditions and grows for most of the year. It has two flowering periods at low elevations, but can tolerate a wide elevation range. The species also benefits from the absence of seed predators, though the introduced broom seed beetle *(Bruchidius villosus)* does induce significant seed losses at some sites (Syrett 1996). Broom often forms invasion-resistant monocultural stands for several decades (Williams 1981) which presumably alters soil chemistry, although N_2-fixation rates have not been measured under New Zealand conditions (McQueen *et al.* 2006).

Phenology

Germination take places in the spring and autumn and these two stages vary yearly (Hosking *et al.* 1996). In areas where water is a limiting factor, seedlings emerging in the spring cannot survive the summer without the presence of vegetation cover (Harrington 2007). Flowering occurs from October to December and after spring in New Zealand (Williams 1981) and Australia (Parsons and Cuthbertson (1992), see Hosking *et al.* (1996)).

1.2.7 Reproduction and growth

Flowering and pollination

Broom plants reach maturity and begin to flower at around 2–5 years old in Australia (Smith & Harlen 1991; Sheppard *et al.* 2000; Sheppard *et al.* 2002), at 3–4 years old in Washington (USA) (Parker 2001) and at 2–3 years of age in British Columbia (Zielke *et al.* 1992). Flowering age can be affected by grazing and the presence of grass competition following seedling establishment increased age at flowering by at least one year, while disturbance decreased age at flowering by at least one year (Sheppard *et al.* 2000).

Pollination of broom is dependent on the presence of bees including bumblebees (*Bombus terrestris*) (USA, Parker (1997)) and honeybees (*Apis mellifera* L.) (Japan, Suzuki (2000)), but only 40% (in USA) and 3% (in Japan) of flowers are visited and pollinated by the combination of both bees (Parker 1997; Suzuki 2000). In south-east Australia, field experiments conducted at Barrington Tops National Park (NSW) using hand out-cross pollination treatments imply pollinator limitation of individual broom plants: 84% of bagged flowers allowed a single honeybee visit set fruit; whereas only 35% of open-control flowers set fruit (Simpson *et al.* 2005). In New Zealand, the most common pollinators were honeybees (*A. mellifera*: 70% of all visits), followed by bumblebees (*B. terrestris*: 17.1%), the native bee (*Lasioglossum sordidum* Smith: 10.2%) and others (Paynter *et al.* 2010).

Pollination limitation seems to have potential to control broom in New Zealand but this requires more research. The first work by Paynter *et al.* (2010) found that reduced pollination through absence of honeybees can reduce broom seed set to levels at which biological control can be more effective. An invasive Varroa mite (*Varroa destructor*), which has caused honeybee decline in New Zealand, may cause pollinator limitation. They suggested that to capitalise on the impact of Varroa mite on feral honeybees, improved management of commercial beehives, such as withdrawal of licences for beekeepers to locate hives on Department of Conservation land, could be used as part of a successful integrated broom management programme at many sites in New Zealand (Paynter *et al.* 2010).

Seed production and dispersal

Seed production in broom is highly variable (Waloff & Richard 1977; Smith & Harlen 1991; Bossard & Rejmánek 1994). This variability exists among plants (Waloff & Richard 1977), among years (Waloff & Richard 1977; Smith & Harlen 1991) and among populations (Parker 2000). Broom is a prolific seed producer and seed bank species (Bossard 1993; Peterson & Prasad 1998) with seed production begins first in the third year but the number of flowers to develop into fruits is usually tiny in these very young plants (Smith & Harlen 1991). When plants mature (about 3–8 years later), it could produce 2000–3500 pods, encasing up to nine seeds per pod (Zielke *et al.* 1992). Seed production is cyclic with seasons of heavy seed productions being followed by one of low seed production (Waloff & Richard 1977).

Broom seeds may be dispersed by ants (Bossard 1991; Smith & Harlen 1991). In Australia, short dispersal by ants was recorded over about 1 m and other dispersers may be horses, streams, machines and vehicles for longer distances (Smith & Harlen 1991).

Seed dormancy and factors controlling seed dormancy and germination

Seed dormancy is a phenomenon thought to be important to plant dynamics such as seed germination and seedling recruitment, survival and fate. Harper (1977) defined dormancy as “the normal state of seeds in the soil in which seeds are dormant when they are not germinating”. Based on this definition, seeds are recognised by three types: innate dormancy (seeds are born dormant), induced dormancy (seeds achieve dormancy) and enforced dormancy (seeds have dormancy thrust on them). However, there is no unanimity about the definition and significance of dormancy phenomenon in the literature (Vleeshouwers *et al.* 1995).

Understanding the factors controlling dormancy breakage of weed seeds is of importance to management and control of invasive weeds. Leguminous weed species like broom and gorse have a hard seed coat so that the seeds can persist in the soil for a long time even if further production of seeds is prevented (Moss 1959) or conditions are not suitable for regeneration. Broom has a substantial and long-lived seed bank (Bossard *et al.* 2000) and like other leguminous shrubs, broom seed is dormant due to impermeability of the seed coat to water and oxygen to the embryo (Abdallah *et al.* 1989) thus the seed is hard to germinate unless it is scarified (Bossard 1993).

Scarification methods and factors controlling dormancy and germination

Several artificial scarification methods can be used to break down, remove or increase the permeability of the legume hard seed coat. These can be divided into two types: (1) mechanical means by using clipping, abrasion with sand paper, immersion in hot water and exposing seed to heat and (2) chemical ways via using strong oxidative agents like sulphuric acid, sodium hypochlorite and liquid nitrogen (Martin *et al.* 1975; Wan Mohamed 1981; Abdallah *et al.* 1989; Tarrega *et al.* 1992).

Seeds with physical dormancy have specific regions of the seed coat that become permeable to water. Temperature is the most important environmental factor causing hard seeds to become permeable. High temperatures and high daily fluctuations cause softening of hard seed coats of species that germinate in late spring, summer or autumn whereas low temperatures during winter appear to be responsible for softening of hard seeds that germinate in early spring (Baskin & Baskin 1989).

Previous work on the effects of fire and heat on the leguminous seed germination was carried out by Martin and Cushwa (1966) (as cited in Martin *et al.* (1975). They hypothesised that germination of legume hard seeds would be increased by exposure to heat and developed a hypothetical germination curve (Fig. 1.2) showing four ranges of germination: a range of low germination at low temperatures, a range in which germination quickly increases with temperature as seed dormancy wears off, a range of constant high germination, and a range of rapid decrease in germination as high temperatures become damaging.

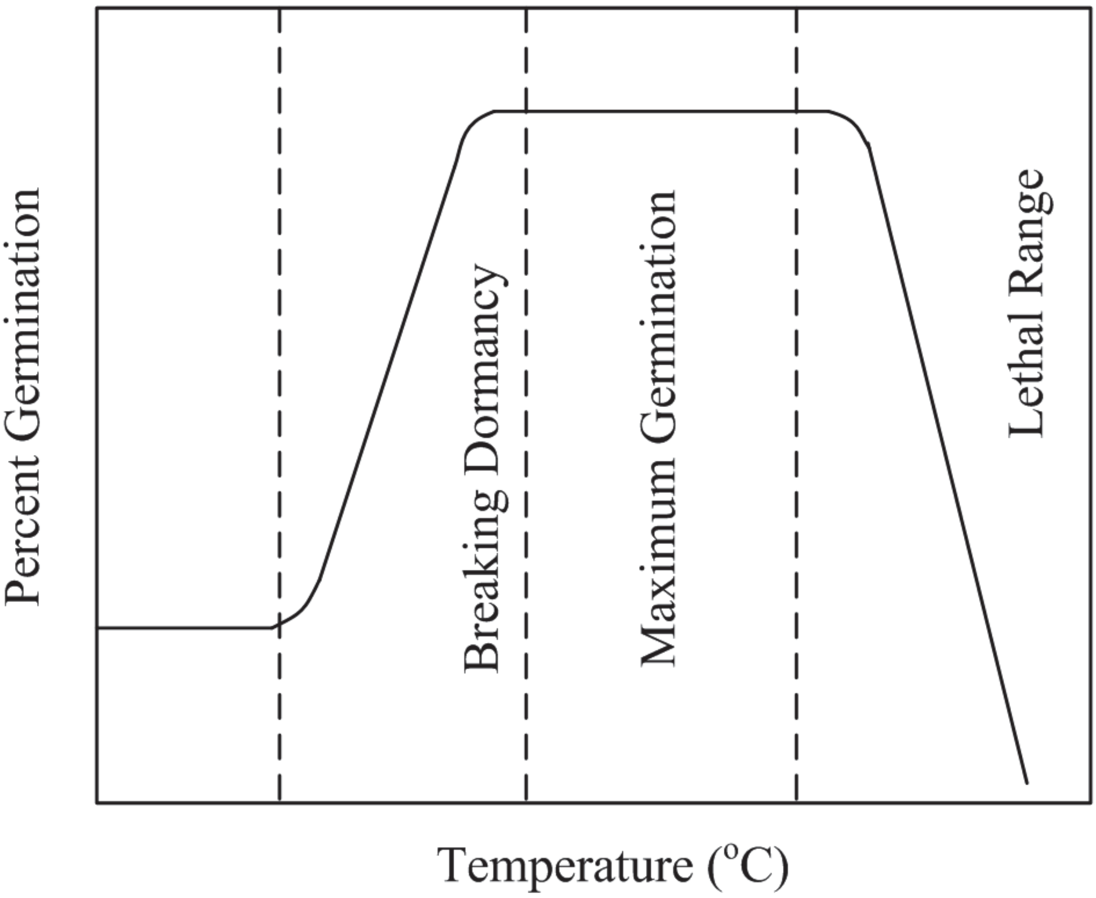


Figure 1.2. Hypothetical germination curve of hard seeds showing the time at which dormancy is broken (adapted from Martin and Cushwa (1966), cited in Martin *et al.* (1975)).

Martin *et al.* (1975) investigated the germination response of 18 legume species to moist and dry heat and found that moist heat increases germination in eight species and dry heat increases germination in seven species. However, in some species, the seed coat may be almost impervious due to its physical and chemical properties and thus be a factor responsible for excluding water and maintaining dormancy.

The characteristic of hard seeds of broom is thought to be similar with that of gorse and therefore much of the work on gorse may be extrapolated to broom. Sixtus *et al.* (2003) determined the proportion of gorse seeds germinated under laboratory conditions with various temperatures, concentrated sulphuric acid (36N) and different times of immersion in hot water and mechanical scarification treatments. They found that the highest germination rate (81%) was obtained from seeds that had been immersed in sulphuric acid for 180 and 210 minutes with incubation at 15°C while hot water immersion did not significantly increase germination and mechanical scarification showed reduced germination (48%).

Ivens (1978) identified factors controlling gorse seeds germination on cleared and un-cleared sites and found that a large proportion of seeds can germinate without stimulus of burning. The most likely explanation for the observed stimulation of germination was thought to be either increased light intensity and temperature fluctuations. However, Ivens (1983) found that light is not required for gorse seed germination and in fact light depressed the germination of seeds extracted from soil.

Ivens (1983) investigated the germination of gorse seeds at various temperatures between 4–40°C on a thermal gradient bar using three sources of seeds: seeds from pods, seeds collected from soil surface and seeds extracted from the soil. It was found that there were a higher proportion of hard (dormant) seeds in seeds from pods than seeds from the trays on the ground while seeds from the soil had little hard seed. The most suitable range of temperatures for gorse seed germination was 15–19°C and this confirmed previous observations by Moss (1959) and Zabkiewicz and Gaskin (1978) which was consistent with field observations of germination peaks in late spring and early summer (Ivens 1982).

Moss (1959) reported that heating gorse seeds in an oven to 88°C for 30 min will stimulate germination. Zabkiewicz and Gaskin (1978) showed that the appearance of numerous gorse seedlings was commonly found on cleared sites and burning with temperatures below 100°C accelerated germination of some seeds while those above became fatal even after short exposures. Results of this study are further confirmed by Harper *et al.* (1961) who examined the germination of gorse to heat of fire using combinations of temperatures and duration of exposure and found that the highest rates of germination were obtained from seeds exposed at 140°C for 5 min but then declined if exposed at 120°C for 10 min. At an Oregon site (USA), fire reduced the number of viable gorse seeds in the soil by 54% (Clements *et al.* (2001).

Baeza and Vallejo (2006) studied the effects of high temperatures (burnings) at different soil depths on germination of *Ulex parviflorus* seeds and indicated that the locations of the seeds in the soil affects the subsequent appearance of *U. parviflorus* seedlings and the highest seedling emergence was found in the seedlings situated at -1 cm (69.2%) and the lowest at -5 cm (7.8%). Highest germination percentages (>80%) were observed in a range of temperatures of 60–120°C for period of 4–6 min and even seeds subjected to temperatures above 120°C for 1 min also showed high and medium germination levels. It is suggested that the maximum germination of this species depends upon a combination of heat intensity and duration as well as the depths of the seeds buried in the soil.

Prior to germination, broom seeds need to swell and thus swelling deteriorates seed coats and allows germination to occur. Swollen seeds can shrink if the seed coat is not damaged and the seed may swell if water is not a limiting factor but it may remain dormant if oxygen is insufficient and temperature is too low (Downey 2002). However, germination cues for broom are not entirely known. Germination trials in the laboratory indicated that scarified seeds required 5 days in a growth chamber (12 h day at 25°C and 12 h night at 12°C) to attain 70% germination (Fogarty & Facelli 1999). Wan Mohamed (1981) indicated that the largest number of broom seed germinated when they had been immersed in sulphuric acid for 5 h. Other experimental trials showed that germination could be promoted by nicking or sanding the seed coat or applying dry heat for 1 min at 130°C or 15 min at 70°C or using hot water over seeds and leaving them to cool to room temperature (Smith & Harlen 1991).

Though light could suppress germination as reported by Smith and Harlen (1991), the effects of light on germination and seed ages were found to be not significant in one study (Bossard 1993). Indeed, seeds were found to germinate in a broad range of light conditions (Downey 2002). While low light levels do not appear to prevent germination, they do influence the growth habit of seedlings (Williams 1981). Daily alterations between freezing and room temperature can suppress germination but do not prevent it (Smith & Harlen 1991).

In an effort to overcome broom seed dormancy, Abdallah *et al.* (1989) used boiling water and liquid nitrogen for periods of 1 sec to 1 min with a selection of combined treatments. They subsequently found that repeated brief (3 or 10 seconds) immersion of seeds in boiling water stimulated rapid seed imbibitions and completely eliminated the hard-seededness and promoted germination, as the rate and final proportion of seeds imbibed were higher in comparison with those of control. The longer treatment tended to decrease the overall rate and final germination percentages compared to the shorter treatment. On the contrary, treatment of dry seed with liquid nitrogen alone also improved seed imbibition and promoted germination but the rate and final percentages were lower compared with those of boiling water treatment. There was, however, no strong correlation between imbibition and germination although it was shown that treatments that improved the rates of imbibition accordingly improved germination performance.

The effect of high temperatures similar to that experienced in natural fires, on seed germination of two woody legume shrubs, *C. scoparius* and *Genista florida*, was examined by Tarrega *et al.* (1992). The seeds of these species were heated from 50–150°C within a range of exposure periods from 1–15 min. No seed could germinate when the temperature reached 130°C or more and the exposure time was 5 min or more. Nonetheless, moderate heat treatments at 70°C and 100°C significantly increased the germination rates relative to controls. *Cytisus scoparius* is clearly more favoured by fire action than *G. florida* with germination rates slightly greater following 100°C for 5 min and 130°C for 1 min. It was concluded that dry-heating the seeds was as efficient as mechanical scarification in terms of final percentage. Results of this study are further confirmed by Herranz *et al.* (1998) who showed the degree of stimulation of germination by thermal treatments obtained for some Mediterranean legumes, i.e. *C. striatus* (Hill.) Rothm., *C. reverchonii* (Degen & Hervier) Bean, *Argyrolobium zanonii* (Turra) P.W. Ball and *Psoralea bituminosa* L. The range of temperature in the soil allows the seeds of each species to find their specific heat requirements but the highest temperatures that promoted germination in these species in a shared habitat were remarkably different.

Bossard (1993) identified response of broom seeds in soil to heating and found that temperatures >150°C or more for 2 min killed the seed and temperature >100°C for 1 min increased fungal infections while temperatures >65°C for 2 min markedly enhanced germination and increased fungal resistance. It appears that temperature provides minimal barriers to germination and that there is no physiological requirement for a cold period or viable day/night temperature range for germination. The only way that temperature prevented germination was through mortality related to intense temperatures and long exposure times.

Thus, broom seeds can germinate in a wide range of temperatures and this may indicate why this species can establish under a wide range of geographic and climatic conditions (Williams 1981). Two defined peaks of autumn and spring germination have been observed in the field (Hosking *et al.* (1998), as cited in Downey (2002)) which may be partly explained by the correlation between germination and rainfall (Sheppard *et al.* 2000). It seems that soil type does not strongly influence seed germination and seedling growth (Williams 1981). Studies by Sheppard *et al.* (2002) found that cultivation increased broom establishment and seedling survival compared with plots where vegetation was not removed by cultivation. On the contrary, Parker (2001) indicated that cultivation did not increase the germination rates of broom at three Australian sites and Bossard (1991) even showed that broom germination in one site in California decreased when the soil was disturbed. These differences could be explained by variations in soil factors such as moisture conditions at the site and the absence or appearance of vegetation covers (Potter & Kriticos 2007).

Growth-chamber studies were conducted by Harrington (2009) to determine effects of temperature regime and cold-stratification period on broom seed germination. Germination was greatest for a dark/light temperature regime of 15/20°C. Initial rates of germination increased as the stratification period increased from 0–60 days, but the final germination percentage after 90 days did not differ significantly among the different stratification periods.

In summary, there have been a series of studies concerning factors affecting dormancy and germination of leguminous hard seed species carried out in both native and exotic ranges. Of the many factors, temperature is considered as the main factor regulating the stages of development and the release from dormancy.

Seed bank, longevity and germination

Broom seeds have a hard seed coat and can be very long-lived under controlled laboratory conditions (Youngman 1951) and are indeed hard to germinate under normal conditions without being disturbed or scarified. Without physical scarification, only small numbers of seeds germinate at any time (Hosking *et al.* 1996) and a large proportion of seeds can remain viable in the soil for more than three years (Smith & Harlen 1991). Therefore, seed longevity can contribute to large soil seed banks in both native and introduced ranges. In the native range, soil seed banks below broom plants varied from 430–10,000 seeds m^{-2} (Smith & Harlen 1991; Hosking *et al.* 1996) while the number of seeds appears to be generally higher in the exotic range, e.g. from approximately 3200 seeds m^{-2} in Victoria (Wearne & Morgan 2006) to 16,675 seeds m^{-2} in Armidale (Smith & Harlen 1991) in Australia and from 1554 seeds m^{-2} in Canterbury (Partridge 1989) to 2649 seeds m^{-2} in Nelson (Allen *et al.* 1995) in New Zealand. Seed- and pod-seeding insects do not appear to have a significant impact on native broom populations in Europe, whereas in Australia these insects may have a greater impact due to reduced numbers of parasitoids that could reduce broom soil seed banks (Hosking 1995).

Fire can stimulate seed germination and reduce the size of the seed bank depending on the intensity and duration of the fire (Smith & Harlen 1991; Rees & Long 1992) but fire does not empty the seed bank (Downey 2000) particularly if the seed is not brought up to the soil surface following disturbances.

Disturbance

Many trials have examined the impacts of disturbance on broom seed germination and seedling survival. Studies by Paynter *et al.* (2000) in UK and France showed that disturbance increases broom germination and seedling survival. Rees and Paynter (1997) predicted a non-linear relationship between disturbance and area infested by broom and found that low intensities of disturbance result in low seedling survival due to the lack of opportunities for broom seedlings to establish under mature broom plants. On the contrary, high levels of disturbance facilitate broom establishment but kill seedlings before they reach reproductive age and can result in seed bank depletion (Paynter *et al.* 2000). However, there is a large range of intermediate intensities of disturbance where broom can persist (Paynter *et al.* 2000).

The variation in responses may be due to site factors (safe site) such as moisture conditions at the site at the time of treatment applications and competing vegetation, i.e. removal of the surrounding vegetation could increase the levels of drought stress experienced by seedlings due to soil temperature variations that result from direct sunlight and radiative cooling, which increases seedling mortality (Smith 2000; Parker 2001). Likewise, sites dominated by strong competitive plant species such as turf forming grasses might display a negative impact on broom seed germination and survival (Parker 2001; Bellingham & Coomes 2003).

Growth and development

Broom plants can grow to 4 m in Australia (Downey 2002) and 3 m in India (Srinivasan *et al.* 2007). Prévosto *et al.* (2004) studied the growth of broom at stand and individual levels in France and found that at the stand initiation stage, broom has a narrow age-class distribution and it rapidly invaded the available space in two to three years, especially at sites which were heavily disturbed and the seeds brought close to the soil surface.

Height growth of broom can be rapid, especially in the first few years (Zielke *et al.* 1992). Strong correlations between age, stem diameter (girth) and height of broom plants have been documented in New Zealand, Australia, France (Paynter *et al.* 2003) and India (Srinivasan *et al.* 2007) and there seems to be some consistency in growth patterns of broom as being uniform over time (Paynter *et al.* 2003; Srinivasan *et al.*

2007). Records of broom growth in New Zealand and Australia include plants growing to 1 m in height in the first year and to 4 m within a few more years (Wilson 1994), reaching 2.5 m in height and 2 cm in stem diameter after only 2 years (Williams 1981).

Plant lifespan

Broom plants can live for up to 25 years (Waloff 1968) but their average life span in one study was approximately 17 years (Waloff & Richard 1977). The longevity of broom plants positively affects the subsequent broom density due to the very high density of seed rain produced over a plant's lifetime. Dense stands that persist longer may result in greater depletion of competing vegetation and their seed banks. Since broom lives longer in its exotic habitats (Rees & Paynter 1997) where there is a lack of specialist insect herbivores (Waloff & Richard 1977), it is possible that insects may be partly responsible for regulating European broom populations. Paynter *et al.* (2003) studied the age structure of native and exotic broom populations by counting the growth rings of broom plants and found, however, that maximum plant ages did not vary significantly between countries. This seems counterintuitive based on the findings of Waloff and Richard (1977). However, few of the populations studied by Paynter *et al.* (2003) contained senescent individuals so the maximum ages they recorded did not necessarily indicate the maximum potential longevity of broom. The probability of major disturbance that kills mature plants may be similar across countries so that few plants survive to their maximum potential age in both native and exotic habitats.

Probability of stand regeneration following plant death

If the soil surface is colonised quickly by competing plants following the death of adult broom, broom seedlings may fail to grow. In France, few seedlings established where broom stands were cut away, facilitating vigorous re-growth of perennial grasses and herbs that had persisted beneath stands (Paynter *et al.* 1998). Paynter *et al.* (2003) discovered that the frequency of broom populations with relatively stable age distributions described by a significant '*reversed-J'* shaped relationship between broom density and plant age significantly varied among countries (highest in Australia (73% of populations) and lowest in Europe (18% of populations)). The result of this study supports the hypothesis that exotic populations are more commonly self-replacing in the absence of large-scale disturbance than the native populations. Following senescence and death, native stands are more likely to persist only in the form of a soil seed bank until the next disturbance events create conditions for the re-establishment of another uniformly aged stand (Rees & Paynter 1997). Conversely, in exotic habitats stands may persist in the absence of disturbance (Sheppard *et al.* 2002).

1.2.8 Modelling the invasive weeds with respect to management and control

Biological invasions are now considered as one of the most challenging environmental and global threats. One of the most important problems facing managers is to find the best strategy to manage invasive species among the overabundance of possibilities (Shea *et al.* 2006) and therefore it is of importance to understand factors that determine the population size and regulate population dynamics in order to apply suitable strategies for management of invasive and weedy species (Halpern & Underwood 2006).

Demographic analyses are widely used in conservation biology to evaluate population performance and to suggest management actions for endangered and rare species (Caswell 2001). These analyses are often based on matrix population models in which individuals are classified into discrete stages according to their stage, size, or age (Caswell 2001). To perform a matrix population model, demographic data of individuals are required for estimating matrix elements, i.e. transition probabilities among stages and fecundity.

Knowledge on demography and dynamics of plants is useful for determining factors and processes affecting their life cycles with the use of models to simulate and quantify the influence of management control options such as grazing and browsing (Hunt 2001; Magda *et al.* 2009; da Silveira Pontes *et al.* 2012), fire (Hoffmann 1999; Brewer 2001; Davis *et al.* 2006), herbicides (Crone *et al.* 2009) and biological control (Davis *et al.* 2006; Dauer *et al.* 2012).

Weed demography and management

Weed demography has become an increasingly important topic for population management, which generally has three goals: conservation, harvest, and control. Although much attention has been paid to invasive species within the last few decades (Sakai *et al.* 2001; Koop & Horvitz 2005), there has been little understanding of invasive population dynamics, especially the factors and processes that contribute to their demographic success across the landscape and over the invasion process (Koop & Horvitz 2005). Ideally, this should be studied using a quantitative approach and modelling techniques. In integrated weed management, a variety of control measures are incorporated at the key stages in an undesirable plant species' life cycle and may include *in-situ* control of invasive plants through herbicide application, grazing regimes and the incorporation of biological agents as folivores and herbivores (McFadyen 1998; Briese 2004; Gross *et al.* 2010). The selection of effective weed biological control agents also requires an understanding of the structure of plant demography and plant response to herbivory (Raghu *et al.* 2006). The main objective in weed biological control is to use host-specific insects/pathogens to reduce the growth and/or spread of weed populations to achieve an *a priori* for defining management success (van Klinken & Raghu 2006).

Matrix models for invasive plants

Several kinds of models quantifying the relationships between plant and herbivory, defoliation and pollination have been used for exploring demography of invasive plants. One of the most important tools is the matrix demographic model which is used to understand how factors affect individuals (Caswell 2001). The matrix model is based on a matrix of life-history parameter values (projection matrix) multiplied by a vector of population size (age, size or stage-structured). A projection matrix summarises the life history of a population through the estimates of fertility (recruitment), survival and probabilities of transitions between stages in an $n \times n$ matrix and in so doing can predict the dynamics of populations. The demographic importance of seedling survival varies substantially among the different species and habitats, but often, it is an especially high seedling survival that plays the key role in facilitating invasion. However, in other species it may be high survival in the later stages, i.e. juveniles and adults, which drives population explosions.

Models of plant population dynamics have been used to predict the effects of introduced biological control agents on the population size of the target weeds or to compare the population growth dynamics of invasive plants with those of other native species (Lonsdale *et al.* 1995; Rees & Paynter 1997; McEvoy & Coombs 1999; Parker 2000; Rees & Hill 2001; Buckley *et al.* 2004; Koop & Horvitz 2005; Stokes *et al.* 2006). These include (1) *simulation models* which are based on individual populations that can vary depending on survival and reproduction functions estimated from field studies, (2) *analytical models* in which functions derived from simulation models or field data are used to depict the population processes, and (3) *matrix models* that depends on life table studies (Myers & Bazely 2003).

Matrix models can help to analyse potential changes in a population due to exploitation or other factors explicitly represented in the projection matrix (Jiao *et al.* 2009). They are often used by managers and conservationists as management tools to assess population health and trends, set priorities and evaluate management options (Fisher *et al.* 1986; Duncan *et al.* 2009). Such models have been used in conservation (Crouse *et al.* 1987; Mills *et al.* 1999; Saether & Bakke 2000; Fieberg & Ellner 2001; Armstrong & Ewen 2002; Mollet & Cailliet 2002; Yearsley 2004), forest management (Olmsted & Alvarez-Buylla 1995; Olson *et al.* 2004; Shimatani *et al.* 2007), to understand the role of disturbances such as fire (Silva *et al.* 1991; Hoffmann 1999; Kohira & Ninomiya 2003), and for quantifying individual variability and environmental stochasticity (Pfister & Stevens 2003). The spread of non-native plant species and associated impacts on native ecosystems (Chapin Iii *et al.* 2000) has resulted in the development of many different strategies to manage invaded plant communities (Chapin Iii *et al.* 2000; Davis *et al.* 2006). Of the important approaches, biological control of weed programmes are considered as a potential alternative for the costly, short-term and laborious applications of chemical, mechanical and physical methods. Biological control programs are successful if the host-specific control agents are able to reduce plant population growth rate (λ) below replacement rates (Davis *et al.* 2006).

Hunt (2001) used a size-structured matrix population model to evaluate the effects of sheep grazing on demography and long-term population dynamics of a perennial shrub, *Atriplex vesicaria* in South Australia. The four size classes were: (1) *seedlings* (plants that were 4 cm tall); (2) *juveniles* (plants more than 4 cm tall); (3) *sub-adults* (plants less than 10 cm tall but with a woody stem greater than 3 mm basal diameter); and (4) *adults* (plants larger than 10 cm tall) (Fig. 1.3). Results from time-invariant matrix population models indicated that the *A. vesicaria* population was in decline over much of the study paddock, but the rate of decline was greatest nearer to the water point (population growth rate $\lambda = 0.8$). Decreases in adult survival and recruitment made the largest contributions to reductions in the population growth rate. However, there were spatial patterns centred on the water point in the degree to which particular demographic processes contributed to these reductions, because of a grazing gradient and the differential sensitivity of demographic processes to grazing. Thus, decreases in recruitment contributed to reductions in the population growth rate at greater distances. The large contribution of adult survival to the population growth rate in *A. vesicaria* suggests that minimizing the mortality of established adults should be a priority for management.

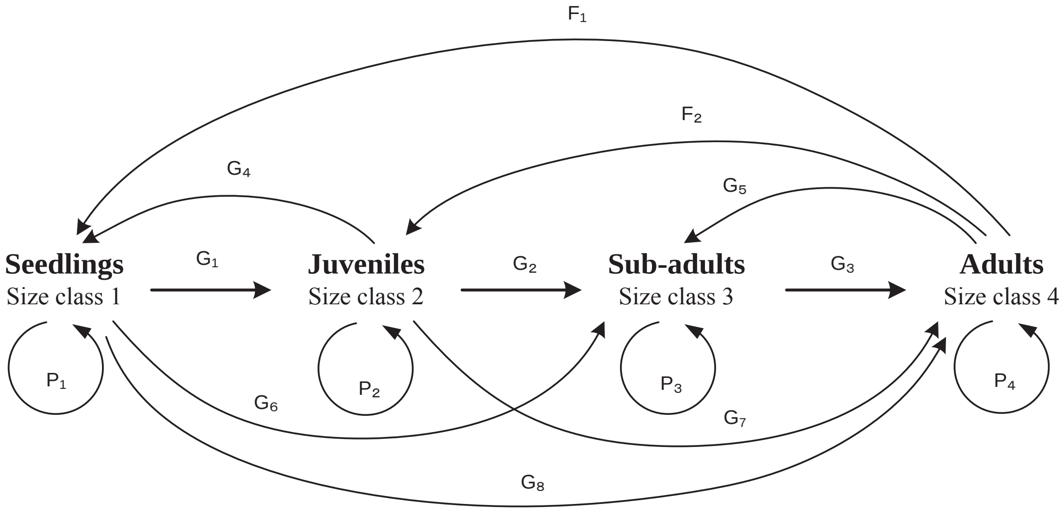


Figure 1.3. Example of a size-structured matrix population model of *Atriplex vesicaria*, of which P = survival, G = growth, F = fertility (i.e. reproduction) (adapted from Hunt (2001))

Broom population dynamics

Broom has been a topic of several modelling exercises (Myers & Bazely 2003), including *matrix models* which assess the population growth, *integro-difference equation models* which measure the spread speed and *lattice models* which evaluate the equilibrium occupancy (Rees & Paynter 1997; Parker 2000; Stokes *et al.* 2006). The most typical model is of the kind developed by Rees and Paynter (1997) in which simulation and analytical models were both used to explore broom population dynamics in Britain. Their simulation model was based on a large number of identical sites in which the simulation is spatially explicit and incorporated local competition, asymmetric competition between seedlings and established plants, a seed bank, local seed dispersal, and an age-structured established plant population. The analysis indicated that when broom colonised all suitable sites with probability = 1, the fraction of sites occupied by broom is determined by only three parameters: the probability of disturbance, the probability a site becomes suitable for colonisation following plant senescence, and the maximum longevity of adults. In exotic habitats, where individual broom plants were allowed to produce several thousand seeds, differences in these parameters were cited as the most likely reason why broom populations are weedier than in the native range. The results of this modelling demonstrated that differences in *disturbance, longevity and the probability of stand regeneration following plant death* explain the disparity in abundance between exotic and native populations (Rees & Paynter 1997).

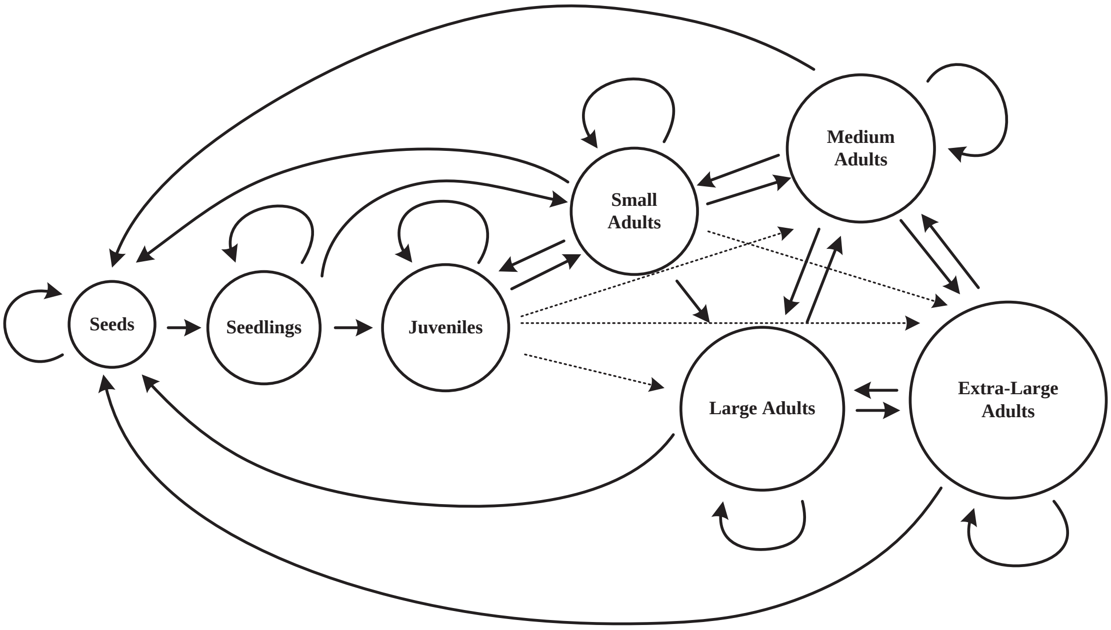


Figure 1.4. Life cycle of broom in Washington State (United States), showing all possible transitions (adapted from Parker (2000)).

Parker (2000) used a projection matrix model to summarise transition probabilities between life stages of two populations of broom, one in an urban site and the other, a prairie, on the west coast of North America (Fig. 1.4). The form of this model was $\mathbf{n}_{(t+1)} = \mathbf{A}.\mathbf{n}_{(t)}$ in which $\mathbf{n}_{(t)}$ is a vector of stage abundance at time t and $\mathbf{A}$ is a matrix of a_{ij} values that represents the contributions of each stage to all other stages. The eigenvalue λ of $\mathbf{A}$ shows the rate of increase at the stable age distribution. In this study, Parker established permanent plots, mapped over 3000 plants, and classified them as seeds, seedlings, juveniles and or into four adult size classes. Fecundity and the probability of transition from one stage to another were determined by repeated sampling. To assess the potential effect of seed-eating insects on these broom populations, Parker manipulated the fecundity values and generated hypothetical λ's for the slowest growing population. She concluded that a seed-eating insect would need to reduce reproduction by as much as 99.9% in the fastest growing population to halt the expansion, and would need to reduce reproduction by 70% to stop even the slowest growing population. Parker's model has been useful in identifying different factors affecting dynamics of established and invading populations (Myers & Bazely 2003).

Stokes *et al.* (2006) evaluated the impact of a proposed introduction of an invasive pollinator (bumblebees) on broom in Australia using three different types of models: a matrix model for assessing population growth, an integro-difference equation for spread seed, and a lattice model for equilibrium occupancy rates. They used available demographic data from an Australian population to parameterise two of these models. They predicted that increased seed set due to more efficient pollination would result in a significantly higher population growth rate ($\lambda = 2.204$) in the density independent matrix model, whereas in contrast, simulations of enhanced pollination scenarios had a negligible effect on equilibrium weed occupancy in the lattice model. This was attributed to strong micro-site limitation of recruitment in invasive broom populations observed in Australia and incorporated in the lattice model. Their work was an example showing the importance of integrating modelling approaches in quantitative risk assessments of pollinator importations.

Magda *et al.* (2009) used a matrix demographic model using data from broom populations collected over five years in heathlands that had established on formerly permanent grasslands in Europe. They found that the population growth rate (λ) of broom on these sites was very high and not limited by seed production in bad years, and that the early life stage survival (of seedlings and juveniles) had the greatest impact on population growth. They concluded that the juvenile stage appears to be one of the most strategic targets for population control (by e.g. grazing) since it combines a high degree of sensitivity in terms of population demography, good palatability for domestic animals and easy accessibility within the management scheme.

Paynter *et al.* (2010) used the broom equilibrium occupancy model developed by Rees and Paynter (1997) to explore interactions between pollination and biological control under a range of New Zealand scenarios. Their model demonstrated that 73% seed destruction, combined with an absence of honeybee pollination, could cause broom extinction at many sites and, where broom persists, reduce the intensity of treatment required to control broom by conventional means. Nevertheless, seed rain was predicted to be sufficient to maintain broom invasions over many sites in New Zealand, even in the presence of the Varroa mite (*Varroa destructor*) and *B. villosus*, largely due to the continued presence of commercial beehives that are treated for Varroa infestation (Paynter *et al.* 2010). An improvement in the ways that commercial beehives are managed in broom-infested areas could help achieve this goal.

da Silveira Pontes *et al.* (2012) simulated the impact of different levels of browsing intensity on a key demographic parameter (survival of juveniles) of broom in order to control population growth, and designed a browsing management strategy focused on this target stage. Three browsing intensities, representing pertinent management practices, were simulated for juveniles (two years old) in a broom population. Standard matrix modelling was used to analyse the impact of browsing on changes in population growth rate (λ), and the results were 6.34 (no browsing), 2.26 (light browsing) and 0.85 (heavy browsing). Therefore, the natural expansion of broom populations may be slowed by light browsing or even reversed by heavy browsing ($\lambda < 1$). They confirmed that focusing browsing on juveniles is an efficient strategy for controlling broom dominance. Shrub control strategies should therefore target early-growth-stage populations and repeat the browsing strategy at the same intensity over several years to achieve cumulative effects (da Silveira Pontes *et al.* 2012).

1.2.9 Management and control of broom

Many different strategies have been applied in the management and control of broom invasions: (1) herbicides (Hosking *et al.* 1998; Clark 2000), (2) burning (Robertson *et al.* 1999; Clark 2000; Downey 2000; Srinivasan 2012), (3) cutting and mulching (Talbot 2000), (4) slashing, hand pulling (Downey 2002), (5) livestock like goats, sheep and cattle (Clark 2000), (6) biological control (Hosking *et al.* 1998; Clark 2000) and (7) other integrated approaches (Balneaves 1981; Prévosto *et al.* 2006; Herrera-Reddy *et al.* 2012) such as the use of grass and legume cover crops to control broom seedling

emergence on forestry sites in New Zealand. Shaben (2007) evaluated the use of sewage biosolids on controlling broom recruitment. Results from the first two years suggested that overall, fewer broom seedlings emerged in the biosolid-treated plots. If these patterns hold, increasing soil nutrients through fertilisation with sewage biosolids could be a useful tool in the control of invasive broom in non-environmentally sensitive sites.
Manual and mechanical methods such as cutting or hand pulling may be effective in controlling broom seedlings and small shrubs but are labour intensive and costly over large areas as repeated actions are required (Hoshovsky 1986; Bossard 1990), and optimal timings are dependent on soil moisture conditions (Oneto *et al.* 2010).

A trial to evaluate the competitive impact of broom on a two year old *Eucalyptus nitens* plantation in Tasmania (Australia) by Barnes and Holz (2000) showed that there was a significant increase in stem volume of at least 23% due to nitrogen and of 49% due to total broom control. They suggested that since broom is shade-intolerant (Hosking *et al.* 1998), to successfully manage broom in forestry plantations, canopy closure has to be achieved at the earliest possible age and applications of nitrogen at years two and three can help achieve this (Barnes & Holz 2000). Sheppard *et al.* (2000) also suggested that broom control is likely to be most effective when the seed bank is low and competitive ground cover is high. However, the success of using these ground covers is based on suitable scheduling of cover crop sowing, tree planting and weed seed germination (Potter & Kriticos 2007) along with the understanding of factors influencing both the ground covers and the controlled weeds.

Biological control of broom has recently been expanded in New Zealand following the importation and release of several new agents (broom gall mines (*Aceria genistae* Nalepa), broom leaf beetle (*Gonioctena olivacea* Förster), and broom shoot moth (*Agonopterix assimilella* Treitschke)) to join the agents established earlier (broom seed beetle (*Bruchidius villosus* F.), broom psyllid (*Arytainilla spartiophila* Förster) and broom twig miner (*Leucoptera spartifoliella*)) (Hayes 2008). The effectiveness and the long establishment of these agents remains limited in New Zealand forest sites, however (Paynter *et al.* 2012). Despite this, biological control appears likely to be the most cost-effective and efficient technique for broom management long-term (Waterhouse 1988) compared with other effective, but labour-intensive methods of control (Alexander & D'Antonio 2003a). In New Zealand, the biological control program was initiated in

1981 (Memmott *et al.* 2005) in the hope of developing an important and cost-effective management tool for broom control that might reduce the need for land owners to pay for more expensive options and difficulty of eradicating large areas of infestations.

The first agent imported was the broom seed beetle (*B. villosus*) introduced in 1987 and reported to destroy approximately 60% of seeds by 1998 (Paynter *et al.* 1998). The second agent was the broom psyllid (*A. spartiophila*) which was released in 1993 but has not yet begun to have any obvious impacts other than in one patch at Lincoln in 2005 (Hayes 2005). In a longer-term experiment in New Zealand, different release sizes (2, 4, 10, 30, 90, and 270) of the psyllid to control broom were made and monitored for five years (Memmott *et al.* 2005). Local psyllid extinction was highest in the first year (compared with later years), and although the probability of extinction in the first year was related to release size, several releases of only one pair of psyllids did result in established populations. Moreover, the persistence of populations after the first year and population growth rates were independent of release size (Memmott *et al.* 2005).

Another agent that arrived by unknown means in 1950 is the broom twig miner (*L. spartifoliella*). This moth is now commonly found throughout the country and some large outbreaks have taken place in recent years, causing some localised but extensive damage to broom. A study at Hanmer Springs indicated that the broom twig miner significantly reduced the growth of infested broom plants over two months (3 cm increment) compared with broom bushes that had been treated with insecticide to remove the twig miner (15 cm increment) (Hayes 2008). However, several studies have indicated that in contrast to the situation in its native range, broom plants in New Zealand remain largely free of specialist insect herbivores despite the establishment of these three agents (Hosking *et al.* 1998; Syrett *et al.* 1999; Memmott *et al.* 2000).

Three additional biological agents have been recently tested and released to try to add to the list of natural enemies that attack broom in New Zealand: a gall-forming eriophyid mite, the broom gall mite, *A. genistae* , which is most abundant in more humid habitats in Europe; a broom leaf beetle, *G. olivacea*; and a oecophorid stem-tying moth, the broom shoot moth, *A. assimilella*, which are active in open habitats in their native range but may also pose a risk for tagasaste (tree lucerne, *Chamaecytisus palmensis* (Christ) Hutch), an introduced plant which is closely related to broom (Jarvis *et al.* 2006). The broom gall mite (*A. genistae*) was first introduced into New Zealand in 2007 (Paynter *et al.* 2012). The dispersal ability of *A. genistae* was investigated to control broom in forestry plantations, where a rapid impact of biological control is required. Preliminary results showed the rate of dispersal (22.2 m year^{-1} in a conifer plantation) is unlikely to be far enough to gain control of broom in forestry (Paynter *et al.* 2012) and further techniques are required to enhance mite dispersal rate.

Thus far, the broom biological control program has made slow progress in New Zealand (Fowler *et al.* 2000). However, in biological control programmes, the uncertainties have to be examined with cost-benefit analysis techniques in which a range of control scenarios must be taken into consideration. The dynamic (bio-economic) model of broom control reported by Odom *et al.* (2005) suggests there may be a case for scaling up biological control of broom in New Zealand. The potential costs of successful biological control of broom should not prevent the introduction of additional biological control agents into New Zealand (Jarvis *et al.* 2006).

1.3 Research objectives

This project aims at finding suitable management schemes to reduce the invasion of broom at early stage of *P. radiata* establishment where broom is more competitive with young pine seedlings. The projects research framework (Fig. 1.5) shows a life cycle of broom in which seed bank is a key component affecting the success of broom invasion and that is a driver for management strategies (herbicides and ground covers).

Specifically, the project has the following objectives:

1. To identify the variability of broom soil seed banks under different *Pinus radiata* stands.
2. To evaluate the germination of broom seed at different depths within the soil, the duration of broom seed dormancy and the ability of unscarified seeds to germinate once dormancy wears off.
3. To assess the effects of disturbance and herbivory on broom seedling emergence and survival.
4. To compare the effects of different ground cover species sown at different rates and times of the year on suppression of broom seedling emergence, survival and

growth and identify factors affecting the success of ground covers in out-competing broom seedlings.

5. To assess the persistence of residual forestry herbicides for controlling the establishment of broom seedlings.
6. To evaluate the effects of selective herbicides on broom seedlings of various ages and the extent of damage from these herbicides on pine seedlings.
7. To assess the effectiveness of integrated management schemes (herbicides and ground covers combined) on controlling of broom seedlings during the first years of *P. radiata* establishment.

1.4 Thesis outline

The thesis comprises seven chapters with five main result chapters. This chapter reviews aspects of broom ecology and management that direct the objectives of the project. Chapter 2 reports the results from three experiments to meet the first three objectives. The effects of ground covers on the suppression of broom seedlings (Objective 4) are evaluated in Chapter 3. Chapter 4 assesses the potential of using residual herbicides for controlling broom seedlings as they germinate (Objective 5). Chapter 5 focuses on selective herbicides for controlling broom seedlings that have already established within *P. radiata* plantings (Objective 6). Chapter 6 applies a real manipulation approach within a *P. radiata* stand using a combination of management options to control broom seedlings (Objective 7). The final chapter synthesises findings from the five results chapters and discusses further potential management options for the control broom in forestry operations (see Fig. 1.5).

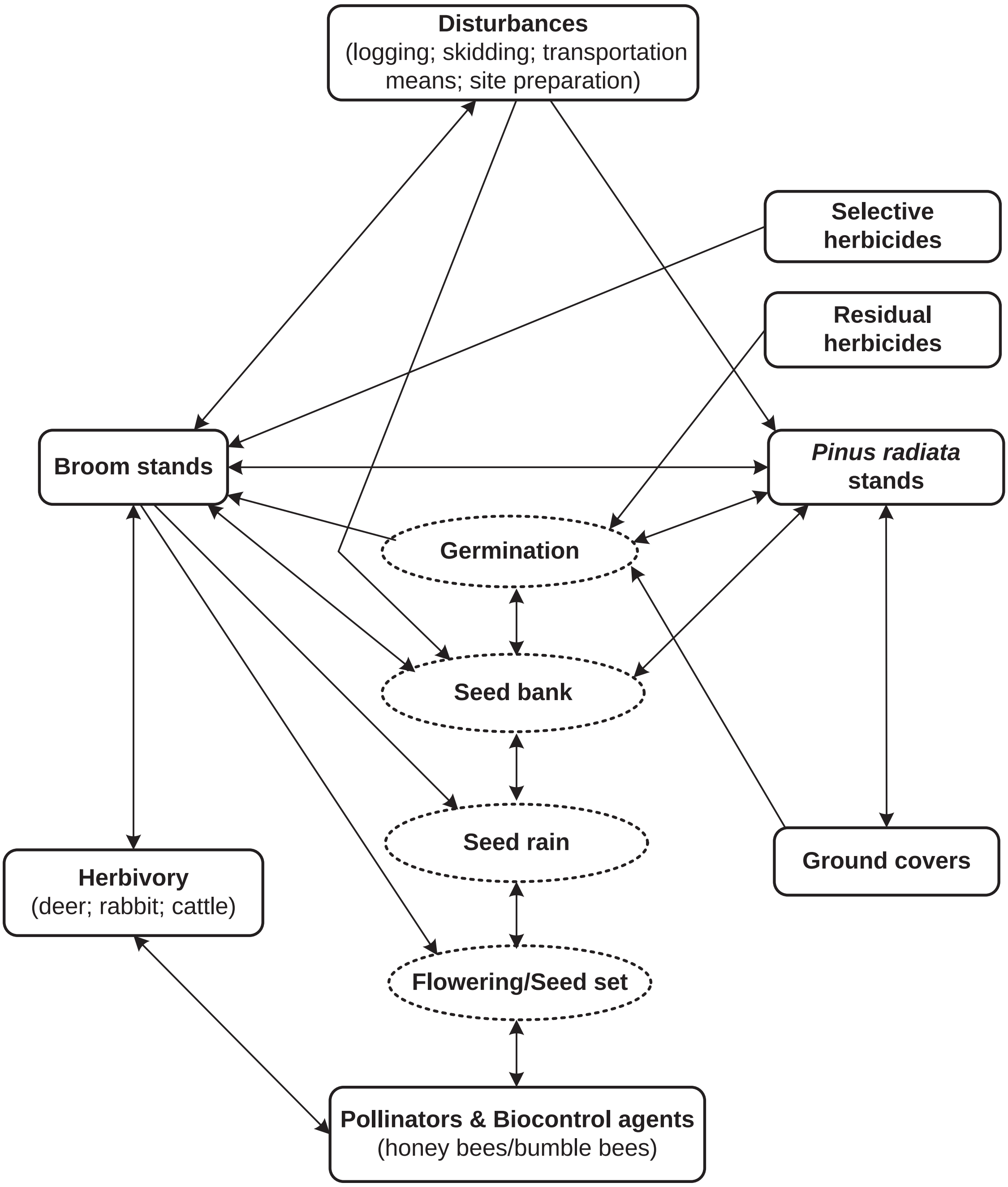


Figure 1.5. A framework showing potential management options with respect to broom invasion stages. Three management strategies that were applied in the research are application of (1) ground covers and (2) residual herbicides to suppress and kill broom seedlings germinating from seed bank, and (3) selective herbicides for killing broom plants.

CHAPTER 2
ASPECTS OF BROOM (*Cytisus scoparius*) SEED BANK, SEED GERMINATION AND SEEDLING ECOLOGY

2.1 Introduction

Successful control of invasive plants mostly depends on reducing the regeneration potential of the target exotic species and other undesirable species that might also be influenced by the removal effort (Alexander & D'Antonio 2003b). When control efforts focus on killing visible individuals, the presence of seed bank can pose the greatest hurdle to successful control. The abundance of viable seeds in the soil determines the likelihood of both immediate re-establishment of the target weed and of future incipient outbreaks (Alexander & D'Antonio 2003b). Soil seed banks are thus comprised of both dormant and non-dormant seeds persisting at varying depths within the surface soil profile (Davis *et al.* 2008). Seeds in the seed banks are more dynamic than they are often portrayed as a result of abiotic (deep burial, crushing, abrasion, burning and water-logging) and biotic (pathogens and predators) factors that bring seeds from beneath to the soil surface (Chambers & MacMahon 1994). The fate of seeds therefore is an important feature responsible for the success or failure of seedling emergence and survival in the field.

In this chapter, three distinct terms (‘germination’, ‘emergence’ and ‘establishment’) are used to identify stages of seedling development as suggested by Bullock (2000). Germination is the protrusion of some part of the embryo from the seed coat. This is easily seen in the laboratory but is difficult to detect in the field. Emergence refers to the emergence of leaves or cotyledons above the substrate surface following the germination and early survival of the seedling. The processes of germination and emergence and the subsequent survival of the seedling are all combined to describe establishment in the field (Bullock 2000).

Broom is a persistent species as it has a large seed bank beneath broom stands. The size of the seed bank differs among sites and varies depending on management history (Alexander & D'Antonio 2003b). Broom has a substantial and long-lived seed bank (Bossard *et al.* 2000) and, like other leguminous shrubs, broom seed is initially dormant—one that will not germinate under any set of normal environmental conditions (Baskin & Baskin 1989)—due to the impermeability of the seed coat to water and oxygen to the embryo (Abdallah *et al.* 1989)unless it is scarified (Bossard 1993) once external forces suitable for breaking the seed coat occur. As the result, broom seeds that are brought to the soil surface may not all be able to germinate, and seeds that are shallowly buried may not be naturally scarified. The long-lasting impact of broom during *Pinus radiata* management requires a better understanding of seed bank as one of the key component affecting the control success of this species. Up to now, there has been no such research reporting on broom seed bank data in forests compare with other studies conducted in grasslands or under mature broom plants. Therefore, it is nessesary to investigate broom seed bank during a forest rotation in order to predict and impose suitable control options.

Control measures such as fires and ground cover species could prevent the success of broom seed germination and seedling establishment, and herbicides kill seedlings through their activity. Because of the potential importance of vertebrate and invertebrate herbivory in a comprehensive management plan, it is nessessary to understand the effects of herbivory on demographic and production characteristics of broom (Bossard & Rejmánek 1994). Deer and elk browse on young shoot of broom at Redwood National Park (USA) (Bossard & Rejmánek 1994). Grazing by sheep has been found to be a successful case for controlling broom seedlings several months after establishment in New Zealand montane shrubland (Bellingham & Coomes 2003). However, in one study grazing increased broom seedling survival, possibly by reducing competition from grasses (Sheppard *et al.* 2000). These results suggested that the use of grazing to control broom should target young seedlings with the help from grass competition to have a better control. In *P. radiata* sites, however, it is hard to control broom without taking care of the effects of grazing on young pine. It is predicted that sowing a high density of grasses could prevent broom seed germination and survival along with the application of herbicides to remove them from pine.

Chapter 1 has summarised some of the ecological characteristics of broom that may affect the direction and success of control methods. This chapter reports on the results of three studies that (1) assess the changes in broom soil seed bank at various stages of *P. radiata* harvest cycle; (2) determine the effects of disturbance and herbivory on broom seedling emergence and survival; and (3) characterise the dormancy and germinability of broom seeds under laboratory conditions and evaluate the ability of broom seeds to germinate at different soil depths under field conditions.

2.2 Materials and methods

2.2.1 Broom seed bank variability and seed viability under **Pinus radiata** *stands*

This section summarises results from a pilot survey study conducted in three broom-infested *P. radiata* stands to (1) assess the changes in broom seed bank (i.e. seed density at different depths) through a planting to harvest cycle in order to test for a hypothesis that the number of broom seeds in the soil seed banks declines or stays constant at different stages of forest management; and (2) evaluate the viability of broom seeds in each *P. radiata* stand to see proportion of broom seeds that are still able to germinate and pose threats after forest rotations.

Sampling areas

The sampling areas including three *P. radiata* stands, i.e. a recently planted stand (2 years), a young stand (9 years) and a mature stand (30 years), located at the Tree Farm near Bulls, North Island, New Zealand (Figs. 2.1 and 2.2).

Sampling methods

In this study, the seed bank was defined as seeds at or beneath the soil surface and capable of germination (Sagar & Mortimer 1976). In each stand, a single transect was diagonally set up from the edge towards the stand centre on 2 October 2008. The seed bank was sampled by collecting three layers of soil (0–5, 5–10 and 10–20 cm) from ten sampling quadrats at 10-m intervals along each transect in each stand. In each quadrat, three soil cores were taken using a soil core sampler (3 cm in diameter and 40 cm in length) at regular distances apart (20 cm) from the centre to the edge of the quadrat. The soil core size and depths selected in this study followed the suggestions of Thompson *et al.* (1997) and other similar work (Allen *et al.* 1995; Sheppard *et al.* 2002; Alexander & D'Antonio 2003b). Each soil layer was kept in a separate re-sealable plastic bag and transferred to store in a cool room at 5°C before they were processed.

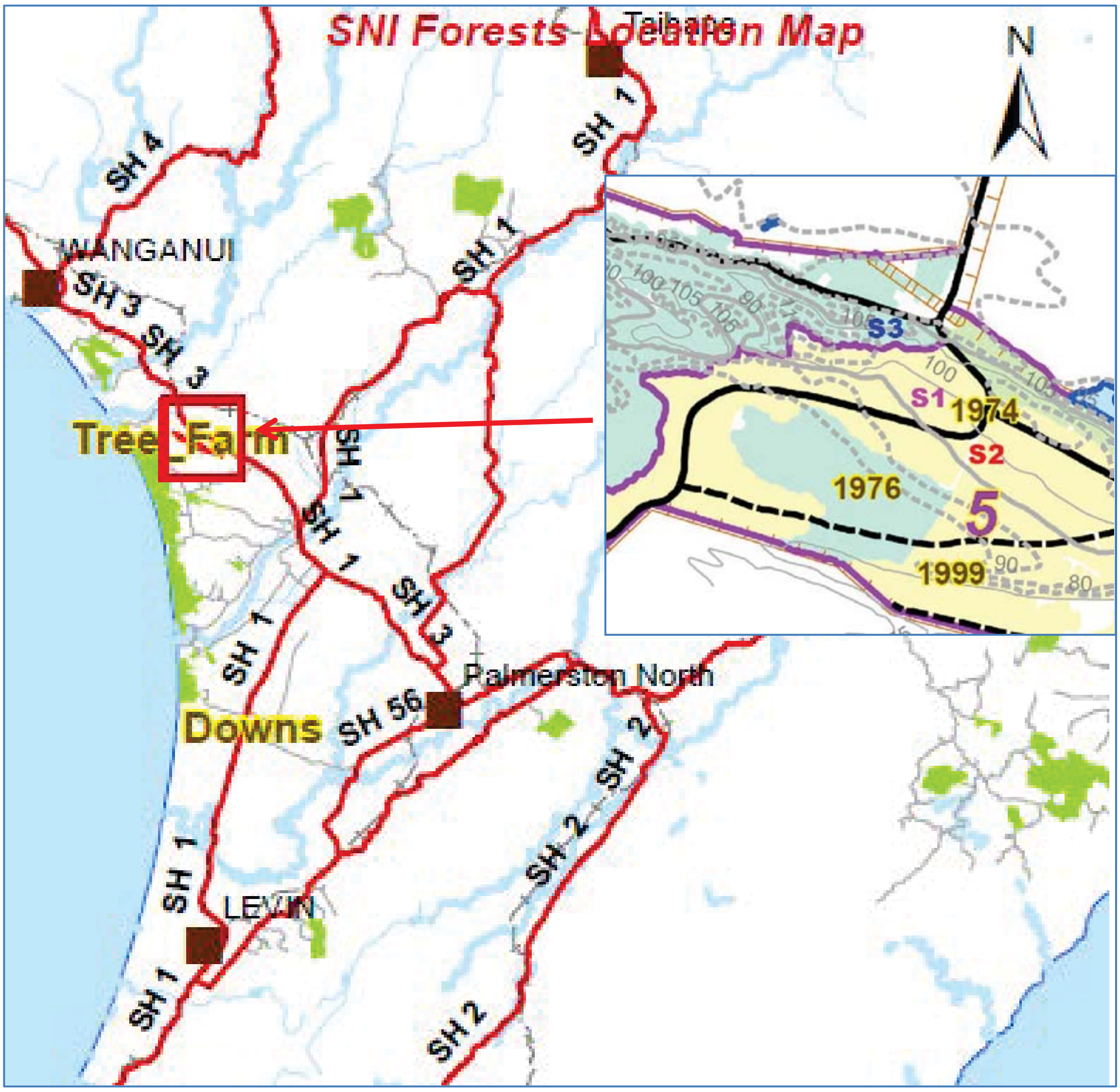


Figure 2.1. Map of the study site (Tree Farm) showing three sampling *Pinus radiata* stands: a 2-year-old stand with many young broom plants and plentiful seedlings (S1) (the trees that were planted in 1974 had been recently felled and re-planted 2 years before sampling), a 9-year-old stand which had a thick cover of mature broom plants which were actively seeding (S2) and a 30-year-old stand in which some live broom plants were visible on the edge of the stand (S3) (this stand due to be felled when sampled).

Figure 2.2. Pictures showing three sampling *Pinus radiata* stands. (A) a 2-year-old stand (S1) (left corner) and a 9-year-old stand (S2) (upper) and (B) a 30-year-old stand (see the caption from Fig. 2.1. for detail).

Seed count and viability test

The soil samples were washed and passed through a set of coarse (2.5 mm) and fine (1.5 mm) mesh sieves to remove roots and pebbles but retain seeds. The residue was then laid out on blotting paper to dry and the seeds extracted, counted and sorted. Each seed was weighed using an analytical balance and its size measured by a micrograph using image analysis software. The seeds from each sample were stored in separate paper bags in a cool room (5°C) before testing for germinability.

A germination test was conducted on 13 November 2008 using seeds separated by depth from each stand. The seeds were randomly allocated to be either hand-scarified by nicking the seed coat with a sharp scalpel, or were left unscarified. All seeds were treated with thiram wet powder (800 g a.i. kg^{-1} as Thiram 80) to prevent fungal attack.

One seed from each treatment was separately placed on each cell of a 25-grid filter paper added with water and kept in a plastic box (17 cm × 12 cm wide and 5 cm deep). The boxes were then placed in an incubation chamber that maintained 16 hours light at 30°C and 8 hours darkness at 20°C as suggested by the International Seed Testing Association (Don 2006). Distilled water was added regularly to the seeds as needed. The trial was run over 28 days and the number of seeds germinated was assessed, counted, and removed weekly. The seeds were classified into germinable (seeds that germinated), dormant (seeds that viable with hard coat but not germinated), and dead (seeds that not germinated and coat softened).

2.2.2 Effects of scarification and burial depth on broom seedling emergence

This experiment was conducted to characterise broom seed germination once dormancy wears off by sowing seeds treated with various scarification methods at several depths in the field. The results obtained from these experiments were used to design the seed-sowing experiments presented later (Chapters 3 and 4).

Seed collection and processing

The broom seeds used for this experiment were collected in November 2007 from soil samples from a broom-invaded *Eucalyptus* spp. plantation (40°23'S and 175°37'E) at the Veterinary Large Animal Teaching Unit, Massey University, Palmerston North. The soil samples were stored in a cool room at 5^{o}C for several days, extracted, and stored as before.

Laboratory experiment

This experiment was conducted to assess the germinability of broom seeds under various scarification treatments to see how well the seeds germinate once the seed coat has been broken. The experiment involved the following seed treatments (Fig. 2.3):

(1) *Hand scarification*: seeds were stored moist in a growth chamber at 15°C overnight to soften the seed coat followed by nicking each seed with a scalpel.
(2) *Mechanical scarification*: seeds were abraded with P100 grade sandpaper placed in the drum of a Forsberg scarifier and rotated for 20 seconds. The rotating time used here was selected as it had previously been shown to give the highest number of germinated seeds in a pilot study testing the effects of time of scarification (0, 5, 10, 15, 20, 25 and 30 seconds) on seed germination (data not shown).
(3) *Untreated control*: seeds were left unscarified as controls.

Following the treatment, the seeds were placed in plastic boxes (17 cm × 12 cm wide and 5 cm deep) on a 25-grid double-layer filter paper and moistened with distilled water. Each box contained 50 seeds (two seeds per cell) with four replicates for each treatment (200 seeds per treatment). The boxes were kept in a growth chamber that maintained 16 hours light at 30°C and 8 hours darkness at 20°C (Don 2006). Distilled water was added regularly (daily) to simulate the periodic wetting and drying experienced by seeds in the field.

Seed germination was monitored weekly and the number of germinants counted and their condition recorded as normal or abnormal and then they were removed from the boxes. Germination was recorded when the radical was 2 mm in length or had perforated the teguments. Mouldy seeds were recorded as dead and removed. Final counts were made after 42 days when all remaining ungerminated seeds were classified as being dead, hard or fresh but ungerminated.

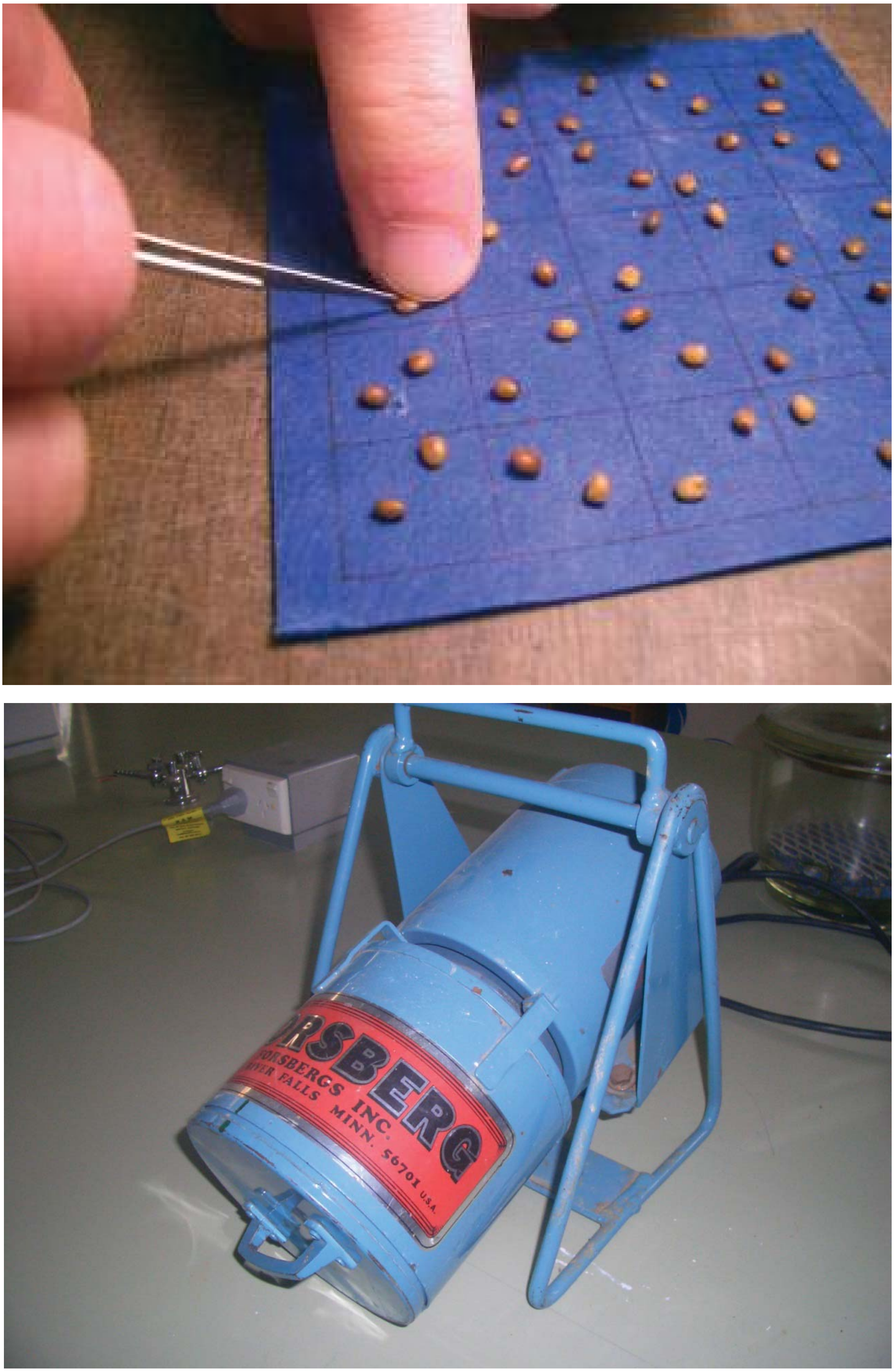


Figure 2.3. Methods of scarification applied for broom seeds: (A) hand scarification and (B) Forsberg scarifier.

Field experiment

Based on the results of the laboratory experiment, a seedling emergence field experiment was conducted to determine the effect of scarification and burial depth on broom seedling emergence. A pasture plot with no history of broom invasion was established at the Fruit Crop Unit (40°23'S, 175°36'E), Massey University, Palmerston North on 29 January 2008 in which seeds were planted at varied depths.

Average monthly temperature and rainfall during the time of the experiment (collected by the Grasslands AgResearch weather station approximately 0.5 km away from the study site) are shown in Fig. 2.4. The maximum daily temperature ranged from 22.6°C in January to 11.8°C in June.

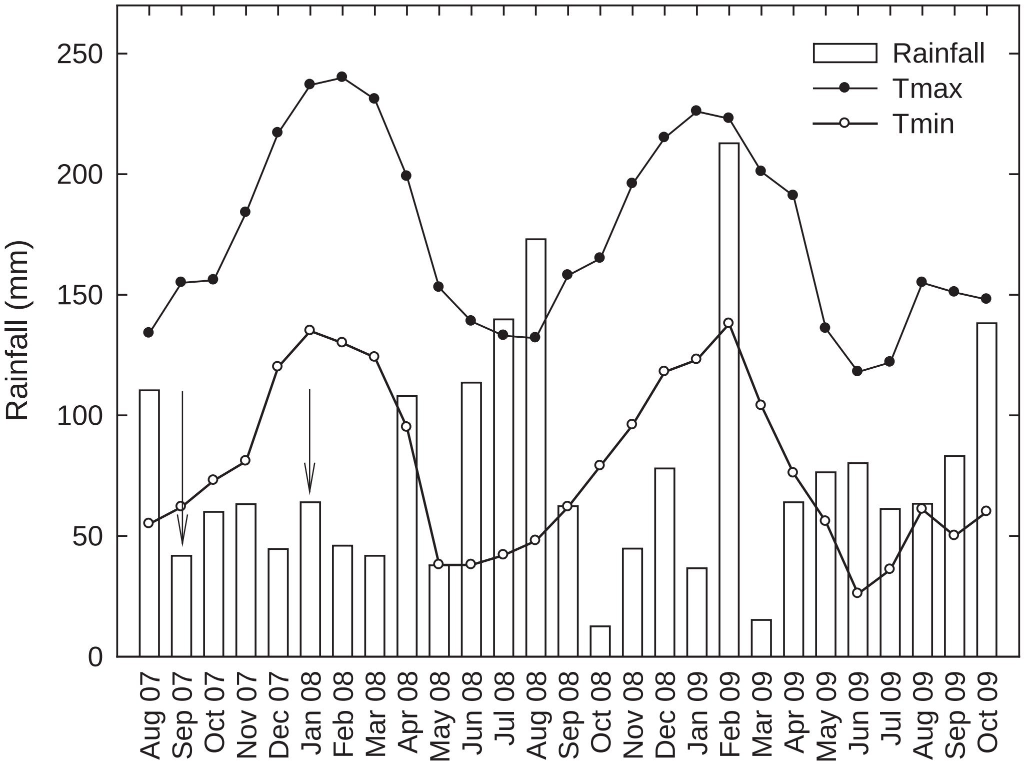


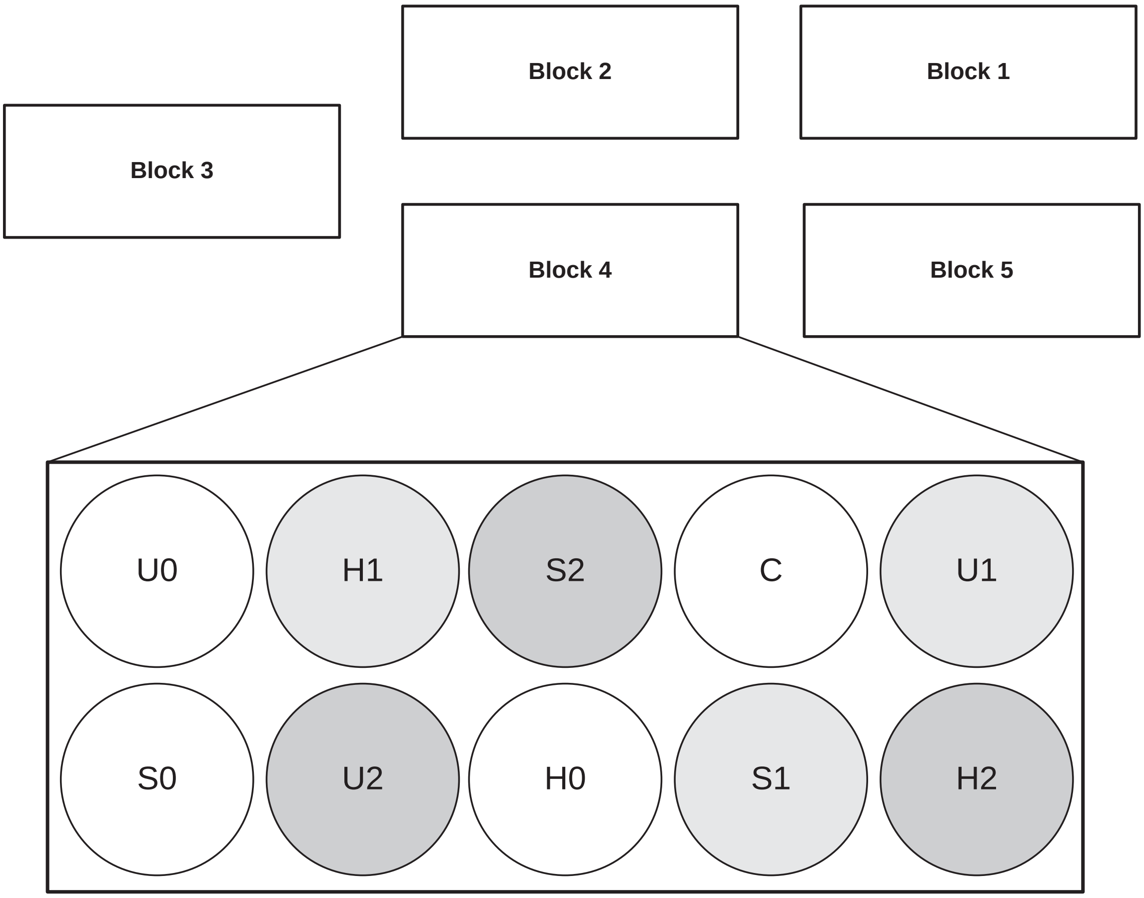
Figure 2.4. Mean total monthly rainfall (mm) and mean monthly maximum (Tmax) and minimum (Tmin) temperature (°C) over the duration of the two experiments. The arrows show the time when each experiment started in January 2008 (Experiment 2.2.2) and September 2007 (Experiment 2.2.3).

The soil was a Manawatu fine sandy loam and samples taken from the trial site had an average pH of 6.1. Olsen-P was measured at 56 μg mL^{-1} and the Na, Mg, K and Ca levels averaged 0.15, 1.14, 0.77 and 8.9 me 100 g^{-1}, respectively. Soil organic matter averaged 5.3% and average CEC was 14 me 100 g^{-1}.

Before the start of the experiment, the site was tilled and any residual vegetation removed using glyphosate (Roundup Transorb at 7 ml L^{-1}). The broom seeds (50 seeds per treatment) used were from the same source as the laboratory experiment. Two factors varied: (1) seed scarification (three groups: hand-scarified, Forsberg machine-scarified (for 20 seconds) and non-scarified); and (2) sowing depth (three levels: at soil surface, 1 and 2 cm underground). A total of nine (3 × 3) combinations were tested in five replicate blocks (250 seeds per treatment). The experimental units consisted of galvanised steel cylinders (15 cm diameter; 10 cm height) buried 8 cm in the soil to preventing the seeds being lost from water flooding (Figs. 2.5 and 2.6), each of which contained 50 seeds. A fine chicken-wire mesh cage covered with a bird nest was placed on each block (Fig. 2.6). After sowing, the soil was irrigated regularly over the first several weeks to ensure germinating seedlings were not water stressed.

Data collection

The broom seedlings that emerged in each treatment were removed and recorded weekly for the first couple of months and later every two weeks. A 20 × 20 cm acetate sheet was used to record the position of each seedling (Fig. 2.6). The experiment ran for 18 months during which all vegetation presented in the subplots was regularly removed using scissors.



H – Hand-scarified seeds

S – Forsberg scarifier seeds

0, 1, 2 – Sowing depths (cm)

U – Unscarified seeds

C – Control (unsown subplot)

▌ – Cage covered with bird nets

Figure 2.5. Layout of the experimental design and a sample block.

Figure 2.6. The experimental design showing five blocks of treatments.

2.2.3 Effects of disturbance and herbivory on broom seedling emergence and survival

This experiment was conducted to monitor changes in broom seedling emergence and survival following soil disturbance, grass competition, and vertebrate herbivory over time (2 years) in a mature stand of broom. This was to simulate what might happen when the forestry sites are cleared (harvested) and grasses sown to suppress broom seedlings from emergence and survival.

Study site

This experiment was conducted in a small broom-invaded *Eucalyptus* spp. plantation (40°23'S, 175°37'E) (the same place for collecting broom seeds used in the Experiment 2.2.2) at the Veterinary Large Animal Teaching Unit, Massey University, Palmerston North from September 2007 to October 2009. Average monthly temperature and rainfall during the time of the experiment (collected by the Grasslands AgResearch weather station approximately 2.5 km away from the study site) are shown in the Fig. 2.4 (see Section 2.2.2). The maximum daily temperature ranges from 22.6°C in January to 11.8°C in June.

The soil was a Halcombe hill and samples taken from the trial site had an average pH of 5.3. Olsen-P was measured at 4 μg mL^{-1} and the Na, Mg, K and Ca levels averaged 0.30, 3.05, 0.43 and 3.6 me 100 g^{-1}, respectively. Soil organic matter averaged 4.0% and average CEC was 14 me 100 g^{-1}.

Before the start of this experiment, a pilot study was carried out on 6 September 2007 in this plantation to test for variability in broom seed location in the soil using two types of soil core samplers in an area assumed to have similar seed densities across it. Samplers tested were: (1) a narrow, long corer (3 cm in diameter and 40 cm in length) and divided into three sections (0–5, 5–10 and 10–15 cm) and (2) a tiller soil sampler (5.3 cm in diameter and 5 cm in depth). Thirty samples were taken for the former corer in three different depths and 10 samples for the latter. The samples were kept in labelled paper bags. The samples were then weighed before being sieved under running water to extract the seeds. These were laid out on filter paper overnight to dry then counted and the number of seeds m^{-2} were calculated and averaged. Results showed that mean number of seeds obtained from the first soil corer at three depths was 2312 seeds m^{-2} (3255 seeds m^{-2} at 0–5 cm; 991 seeds m^{-2} at 5–10 cm and 2689 seeds m^{-2} at 10–15 cm) and 3975 seeds m^{-2} for the second soil sampler. The result showed a high variability in broom seed density over depth in this forest and therefore the first soil core sampler was used for soil sampling in later experiments as it allowed sampling at deeper depths.

Experimental design

This experiment was setup on 7 September 2007 by randomly selecting six mature broom plants (blocks) from a population of broom plants within the *Eucalyptus* spp. plantation. A monitoring plot (0.5 × 0.5 m) was setup under each broom plant and any vegetation present in the plot removed using glyphosate (Roundup Transorb at 7 ml L^{-1}).

The plots were visited again on 21 September 2007 and the following treatments were allocated to each plot: (1) soil disturbed (sprayed with glyphosate, lightly tilled by trowel on 21 September), weeds removed (i.e. all new weeds removed by hand over subsequent months), herbivory protected (cage used to keep away rabbits and livestock); (2) soil disturbed, weeds removed, herbivory unprotected; (3) soil disturbed, weedy (i.e. any new weeds that germinate following initial spraying were not removed), herbivory protected; (4) soil disturbed, weedy, herbivory unprotected; and (5) intact vegetation (i.e. not sprayed with glyphosate initially), herbivory unprotected (Fig. 2.7). Although livestock were generally not present in the area, some animals did get into the site at times from a nearby paddock.

Treatment 5 was used as a control as there was no treatment manipulation applied. The soil was disturbed just once for the other four treatments by digging up the top soil to bring seeds to the surface and all existing ground cover plants were removed by hand. A fine chicken-wire mesh cage was placed on half of the plot to protect seedlings from vertebrate herbivory effects. The plots were visited every two weeks over the first six months and then every month for two years to census seedling emergence and survival. Any weeds that appeared in Treatments 1 and 2 were hand-removed to create bare soil at the time of each census.

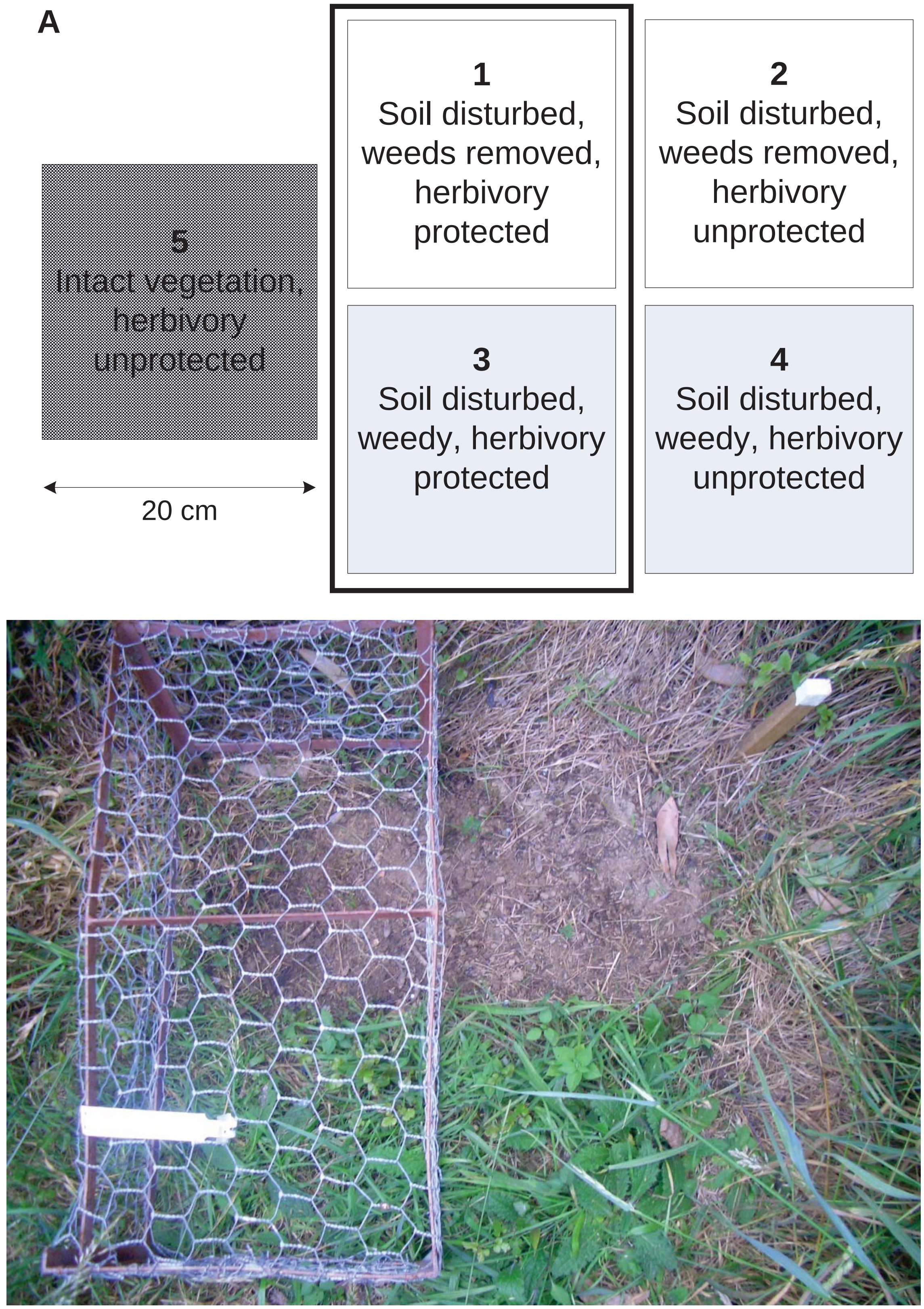


Figure 2.7. (A) Layout of a sampling plot showing five treatments (see the text for details) and (B) a picture showing five treatments in a sampling plot on 27 December 2007 (three months after the start of the experiment).

Data collection and measurements

At each census, the number of broom seedlings that had emerged and the number that survived from previous census in each treatment were recorded using a 20 × 20 cm acetate sheet on which the position of each seedling was recorded and overlain on the plot to determine new seedlings and the survival of previously recorded seedlings. Seedlings that had germinated in the prior census month were classified as old seedlings and seedlings that had germinated in the current census month were recognised by the presence of cotyledons and classified as new seedlings. The percent cover of other plants present in Treatments 2–5 was visually estimated.

2.2.4 Statistical analysis

All statistical analyses were conducted using SAS 9.2 software (SAS Institute Inc. 2008). Treatment effects were considered significant at $P < 0.05$ for all analyses.

2.2.4.1 Broom seed bank variability and seed viability under Pinus radiata *stands*

Preliminary analyses of residuals were performed on the number of seeds m^{-2} at different soil depths and in the different *P. radiata* stands young (2-year-old stand), middle (9-year-old stand) and mature (30-year-old stand) using PROC UNIVARIATE. These revealed a skewed error distribution and so generalized linear mixed models were fitted to the seed count data using PROC GLIMMIX (Willenborg *et al.* 2005; Harrison *et al.* 2007; Fedriani & Delibes 2009) with Poisson error terms (O’Hara & Kotze 2010). The factors “stand” and “depth” and the stand × depth interaction were treated as fixed effects and the replicates nested within a stand treated as random effects. Means and standard errors were calculated using LSMEANS with PDIFF option (Littell *et al.* 2006). To compare the effects of different levels of any significant main factor, the differences between their least square means were calculated. When the interaction between any two factors was significant, tests for the effect of a given factor at the different levels of the other factor (‘‘tests of simple main effects’’) were performed using SLICE option in LSMEANS (Littell *et al.* 2006).

The seed germination data from the laboratory experiment were also analysed using PROC GLIMMIX as above. The Poisson options used accounts for the non-normal error distribution and overdispersed nature of the data that is normal for count data. The correlation between seed size and weight was analysed using PROC CORR.

2.2.4.2 Effects of scarification and burial depth on broom seedling emergence

Data on the seed germination in the laboratory experiment and on the seedling emergence in the field experiment were again analysed with generalized linear mixed models using PROC GLIMMIX as above. Once more, the data were skewed and so binomial error terms were used to test the effects of scarification and depth on seedling emergence with “scarification” and “depth” treated as fixed effects and replicates (blocks) × scarification × depth interaction as random effects. Adjusted means and standard errors were calculated using LSMEANS and back-transformed using ILINK option with the inverse link function to the estimate on the linear scale (Littell *et al.* 2006). To compare the effects of different levels of any significant main factor, the differences between their least square means were calculated. When the interaction between any two factors was significant, tests for the effect of a given factor at the different levels of the other factor (‘‘tests of simple main effects’’) were performed using SLICE option in LSMEANS (Littell *et al.* 2006).

The germination rate (T_{50}, time to reach 50% seed germination) was calculated for all experiments according to the following formula by Coolbear *et al.* (1984):

$$T_{50} = t_i + [(N/2-n_i)\,(t_j - t_i)]/(n_j - n_i) \qquad (1)$$

where: N: the final number of germination by the end of experiment.

t_i: days from start of experimental unit immediately prior to 50% radicle emergence.

t_j: days from start of experimental unit immediately subsequent to 50% radicle emergence.

n_i, n_j: cumulative number of seeds germinated by adjacent counts at times t_i and t_j when $n_i < N/2 < n_j$.

2.2.4.3 Effects of disturbance and herbivory on broom seedling emergence and survival

Two analyses were conducted on seedling emergence and survival: Treatments 1–4 were first analysed as a factorial analysis of variance and then secondly Treatments 2, 4 and 5 were compared to test the effects of grass competition in the presence of herbivory.

Preliminary analyses of residuals were again performed using PROC UNIVARIATE as before and again revealed skewed data typical of counts. As before generalized linear mixed models using PROC GLIMMIX were fitted to the data with Poisson error terms (O'Hara & Kotze 2010) used for the "seedling emergence" and binomial error terms for "seedling survival". "Disturbance" and "herbivory" and their interaction were treated as fixed effects and the block and block × disturbance × herbivory interaction as random effects. Adjusted means, standard errors and other comparison options were calculated with the same procedures used in the Section 2.2.4.1 for seedling emergence and the Section 2.2.4.2 for seedling survival.

For the first analysis, the effects of disturbance and herbivory on total broom seedling emergence (cumulative seedling emergence at the end of the experiment) and survival (proportion of seedling emergence) at the end of experiment were tested by means of analysis of variance using steps in PROC GLIMMIX as mentioned above. Two strategies were used: first, the data on cumulative seedling emergence and seedling survival was analysed separately for each year and then, since the data on seedling emergence and survival in the first 8 months of the experiment turned out to be very low (see Fig. 2.6), a second analysis was performed in which only the data from June 2008 to the end of experiment were used. Results from the first analysis on seedling emergence showed significant effects of year ($F_{1,35}$ = 68.51, P < 0.0001) and disturbance ($F_{1,35}$ = 5.23, P = 0.0284) and year × disturbance interaction ($F_{1,35}$ = 5.99, P = 0.0195) indicating seedling emergence was highly variable between the years.

For the second analysis, which excluded the herbivore-protected plots and compared only Treatments 2, 4 and 5, the same procedures used above were repeated but this time only included the effects of disturbance.

2.3 Results

2.3.1 Broom seed bank variability and seed viability under **Pinus radiata** *stands*

Seed bank

The number of broom seeds in the soil at the Tree Farm varied between 0 seeds m^{-2} to 16,901 seeds m^{-2} for a given soil layer with the maximum number of seeds found in the 0–5 cm soil layer in the 9-year-old stand (Table 2.1). There was a highly significant effect of stand ($F_{2,27} = 31.21$, $P < 0.0001$), depth ($F_{2,234} = 16.97$, $P < 0.0001$) and stand × depth interaction ($F_{3,234} = 269.58$, $P < 0.0001$) on the number of seeds found. The highest proportion of seeds was found at 0–5 cm but the density at this level varied among the stands with the maximum in the 9-year-old stand (3615 seed m^{-2}; Table 2.1) while the 2-year-old stand showed least, perhaps because many of the seeds had already germinated during the pine establishment stage (Table 2.1) and there had been no recent seed rain to replenish the seed bank. Importantly, a large number of seeds (2394 seed m^{-2}; Table 2.1) were still present in the oldest stand (30 years) where there has been no seed rain for some time, showing the persistence of the seed bank. The results showed that most seeds were found at 0–10 cm rather than deeper and therefore there was no need to sample the lower layer in later surveys.

Regarding the distribution of seeds in each stand separately, the number of seeds found at different soil layers in the 2-year-old stand did not differ ($F_{2,234} = 2.96$, $P = 0.0538$), but there was significant differences with depth in the 9-year-old stand ($F_{2,234} = 18.56$, $P < 0.0001$) and 30-year-old stand ($F_{2,234} = 197.68$, $P = 0.0006$). With respect to the depth, the main difference in the seed density was found among stands at 0–5 cm ($F_{2,234} = 7.62$, $P = 0.0006$) and at 10–20 cm ($F_{2,234} = 197.68$, $P < 0.0001$) but not at 5–10 cm ($F_{2,234} = 2.41$, $P = 0.0922$).

Table 2.1. Mean (with standard error of the mean) number of seeds at different depths in three *Pinus radiata* stands in the Tree Farm.

Stand Age (Year)	*Mean (SE) number of seeds m^{-2} at different depths (cm)*		
	0–5	*5–10*	*10–20*
2	516 (208)	235 (235)	94 (65)
9	3615 (766)	376 (202)	0
30	2394 (541)	798 (231)	0

Seed viability

The results of germination test are shown in Table 2.2. Seeds that were left unscarified showed that most seeds were deemed to be either dormant or dead although a small number of seeds germinated without scarification in the 2-year-old stand (11%) and the 9-year-old stand (2%). No seeds germinated in the 30-year-old stand without scarification. This result confirms the persistent dormancy of broom seeds under field conditions.

Most of the seeds that were scarified germinated in all three stands although a number of these were "abnormal" (these seedlings fail to develop a proper root system and remain stunted following germination, possibly because of damage in the scarification process). There were a number of dead seeds in the youngest stand, but very few elsewhere. Including the abnormals with the normals, the largest density of viable seeds was found in the 30-year-old stand, followed by the 9-year-old stand. In this forest, even the oldest stand is well stocked with viable seeds (i.e. up to approximately 14,000 seeds m^{-2}).

Table 2.2. The fate of seeds (%) from the three *Pinus radiata* stands in the Tree Farm after being (A) left unscarified or (B) hand-scarified and left to germinate for 28 days. It was assumed that the abnormals were viable and calculated the number of viable seeds m^{-2} by removing the dead proportion from the total seed densities in Table 2.1.

Treatment	*Stand Age (Year)*		
	2	*9*	*30*
A. Unscarified			
Germinated	11	2	0
Dormant or dead	89	98	100
B. Hand-scarified			
Germinated	45	65	63
Germinated but "abnormal"	22	33	37
Dormant ("hard" and "soft")	0	0	0
Dead	33	2	0
Viable seeds (%)	67	98	100

There was a strongly positive linear relationship between the weight and size of seeds (r = 0.85; Fig. 2.8) but no differences between seed weight and size among depths and among stands. There appeared to be a slight increase in seed size with the age of stand and with increasing soil depth which is possibly due to increased longevity of large seeds, but more data would be needed to properly test this hypothesis.

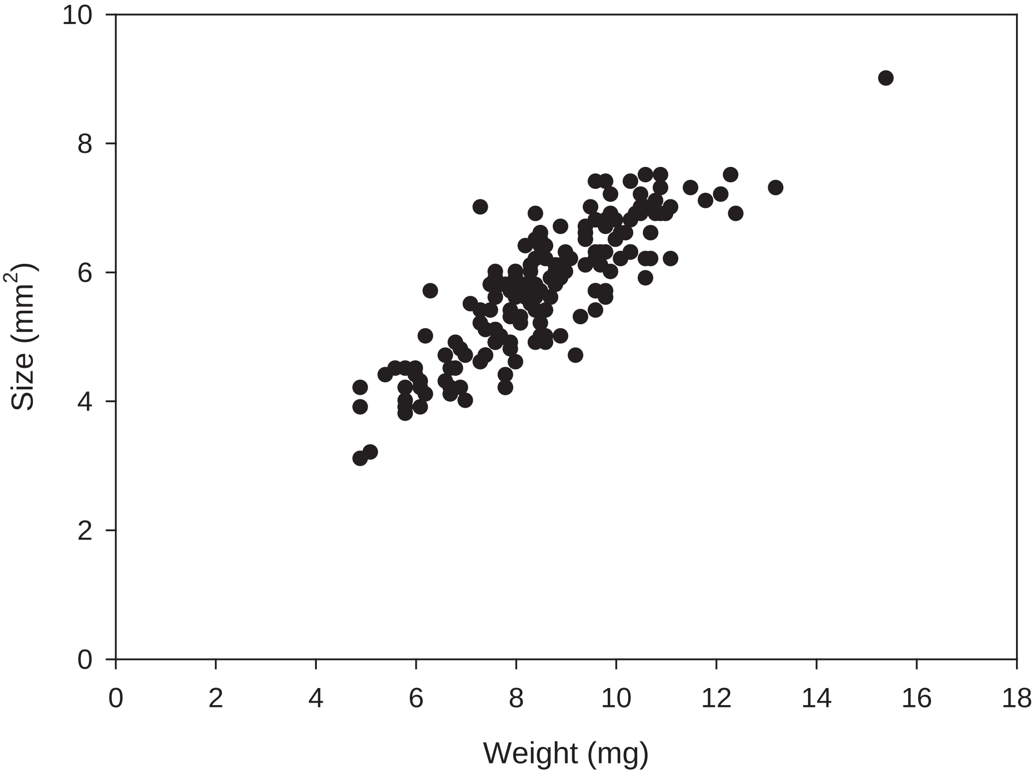


Figure 2.8. Correlation between broom seed weight and size.

2.2.2 Effects of scarification and burial depth on broom seedling emergence

Laboratory experiment

The two scarification treatments had significant effects on broom seed germination compared to unscarified controls ($F_{2,594} = 46.54$, $P < 0.0001$) (Table 2.3; Fig. 2.9). The highest germination percentage was obtained from seeds scarified by machine (98.5%) followed by hand-scarified (78%). Only 1% of seeds geminated in the unscarified treatment with the remainder being dormant. The time taken to reach 50% seed germination for machine-scarification and hand-scarification treatments was 9 and 13.5 days, respectively (Fig. 2.9). The high viability of seeds among the treatments (Table 2.3) is consistent with that found in seeds sourced from the Tree Farm (see Section 2.2.1).

Table 2.3. The fate of seeds (%) 42 days after treatment.

Fate	*Treatment*		
	Hand-scarified	*Scarifier*	*Unscarified*
Germinated	67.5	86.5	1.0
Germinated but "abnormal"	12.0	11.5	0
Dormant ("hard" and "soft")	20.0	1.5	99.0
Dead	0.5	0.5	0
Viability (%)	99.5	99.5	100

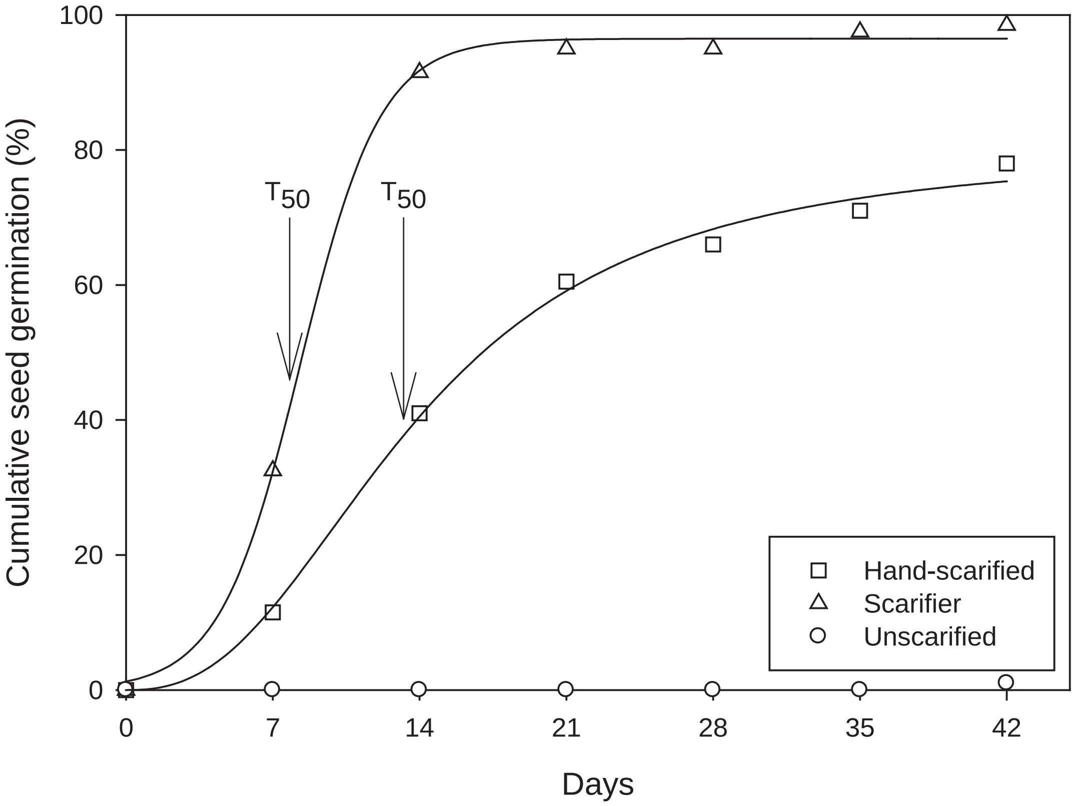


Figure 2.9. Cumulative percentages of seed germination for three scarification methods in the laboratory experiment.

Field experiment

There was again a highly significant effect of seed scarification ($F_{2,31.49}$ = 5.93, P = 0.0065) but not of depth ($F_{2,31.59}$ = 1.48, P = 0.2427) nor was there a significant scarification × depth interaction ($F_{4,31.4}$ = 1.38, P = 0.2643) on seedling emergence over 18 months in the field experiment (Fig. 2.10).

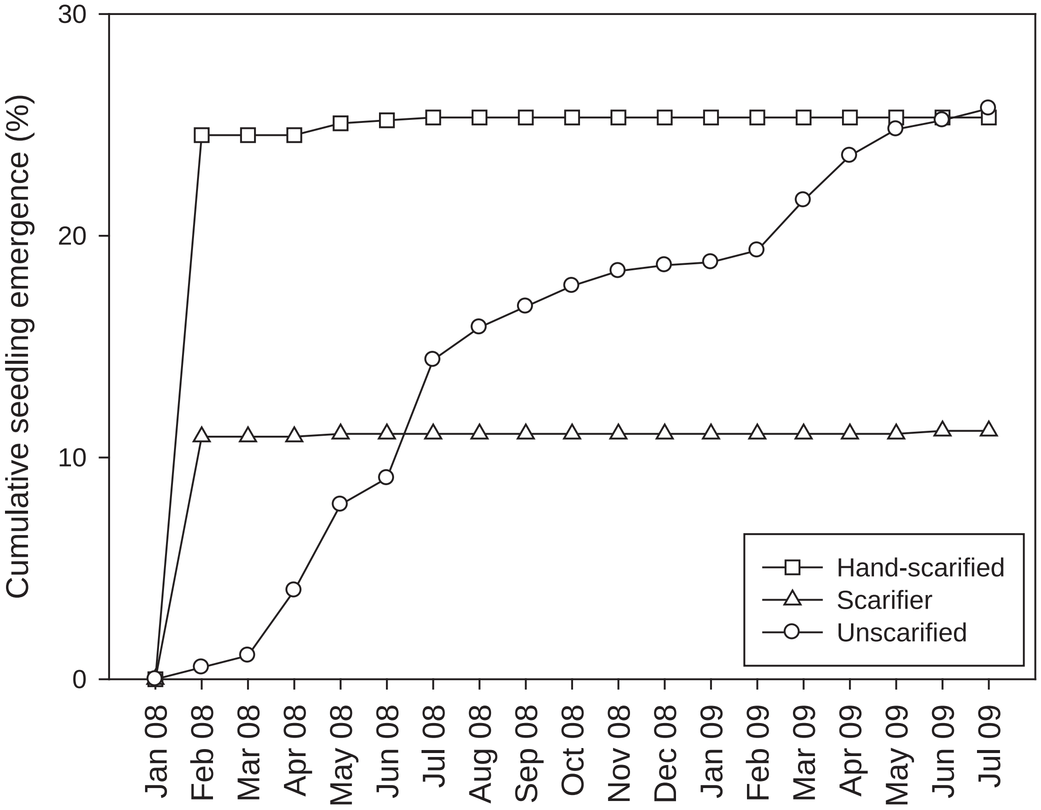


Figure 2.10. Cumulative percentages of seeding emergence for three scarification methods combining from three sowing depths.

Germination occurred quickly (from January to February 2008) for seeds from machine-scarification and hand-scarification treatments but then stopped and the proportion of seeds that had germinated was relative low by the end of the experiment (25.3% and 11.2%, mean of all depths combined), respectively (Figs. 2.10 and 2.11). By contrast, unscarified seeds initially germinated slowly but subsequently germinated at a steady rate and by the end of the experiment had reached a similar level to that of the hand-scarified seeds (25.7%, mean of all depths combined). Overall, none of the treatments performed well, with only relatively low rates of germination (less than 30%). The highest percentage of germination was found for the hand-scarified treatment at 1 cm (37.2%) and lowest for scarifier treatment at 1 cm (9.2%) (Fig. 2.11).

Regarding the speed of germination ($T_{50,}$ time to reach 50% of final germination), both hand-scarified and scarifier treatments required approximately 30 days to reach 50% of final germination. The values of T_{50} for unscarified seeds were 186 days at 1 cm, 207 days at 0 cm and 215 days at 2 cm.

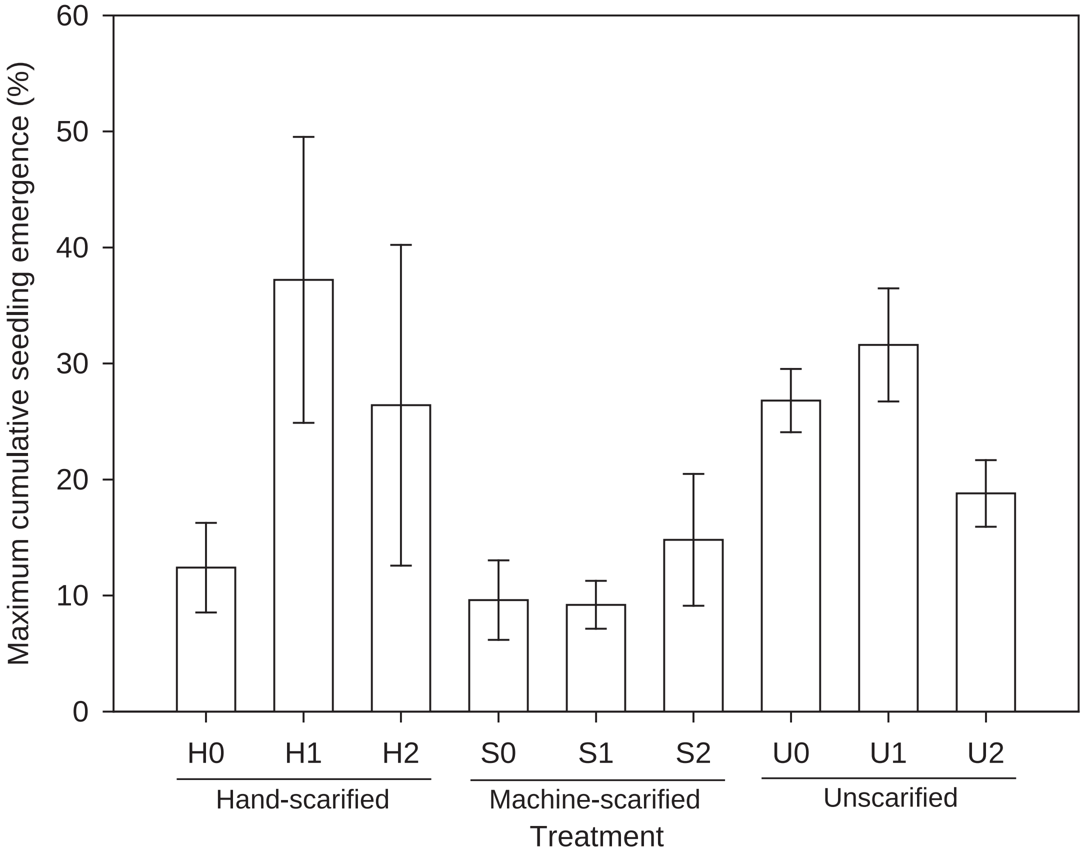


Figure 2.11. Cumulative percentages of seeding emergence for three scarification methods by sowing depths (error bar represents ± 1 standard error of the mean). H0, H1 and H2 were seeds scarified by hand and sown on the surface, 1 cm and 2 cm); S0, S1 and S2 were seeds scarified by machine and sown on the surface, 1 cm and 2 cm) and U0, U1 and U2 were seeds unscarified and sown on the surface, 1 cm and 2 cm.

2.3.3 Effects of disturbance and herbivory on broom seedling emergence and survival

Results on analysis of factorial treatments (Treatments 1–4)

Seedling emergence started slowly for the first eight months (October 2007 to May 2008) in the disturbance/herbivory experiment (Fig. 2.12a) perhaps due to a combined effect of the treatment manipulation and the low rainfall and high temperatures at that time (Fig. 2.4). However, from June 2008 there were increasingly high rates of seedling emergence in all four treatments with the highest in August 2008 (Fig. 2.12a). The cumulative broom seedling emergence after 17 months (June 2008 to October 2009) was not affected by disturbance ($F_{1,15} = 2.67$, $P = 0.1229$), herbivory (protected/not protected in Fig. 2.12a) ($F_{1,15} = 1.66$, $P = 0.2175$) nor was there a significant disturbance × herbivory interaction ($F_{1,15} = 1.17$, $P = 0.2964$). At the end of the experiment, mean cumulative number of seedlings emerging in each treatment subplot (0.04 m^2) ranged from 8 (200 seedlings m^{-2}, intact, unprotected plots) to 25 (625 seedlings m^{-2}, weeded, protected plots). No new seedlings emerged during the final months of the experiment (September to October 2009).

The survival of broom seedlings followed a similar trend but the magnitude slightly differed (Fig. 2.12b). The overall survival of broom seedlings was also not affected by disturbance ($F_{1,14} = 0.39$, $P = 0.5445$) but did differ with herbivory ($F_{1,14} = 6.04$, $P = 0.0277$) although no disturbance × herbivory interaction was found ($F_{1,14} = 2.32$, $P = 0.1501$). At the end of the experiment, mean surviving seedlings in each treatment subplot (0.04 m^2) ranged from 2 (50 seedlings m^{-2}, weeded, unprotected plots) to 11 (275 seedlings m^{-2}, weeded, protected plots) (Fig. 2.12b).

Disturbance treatments without herbivore protection (Treatments 2, 4 and 5)

There were again no difference in both cumulative seedling emergence ($F_{2,10} = 2.83$, $P = 0.1061$) and final survival ($F_{2,9} = 1.30$, $P = 0.3199$) among the disturbance treatments (intact, weeded or weeds left to regrow) over 17 months (from June 2008 to October 2009).

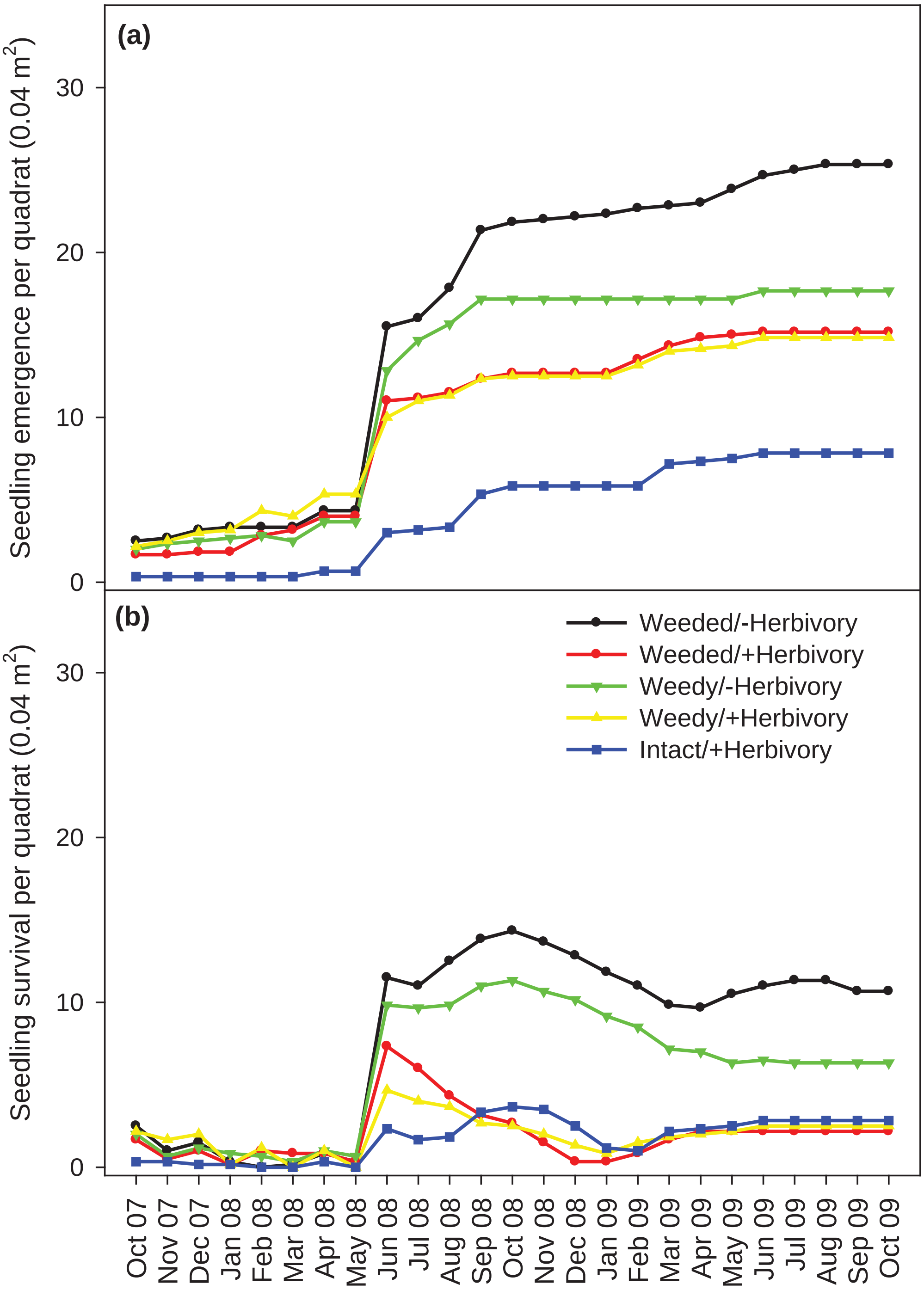


Figure 2.12. The effect of disturbance and herbivory on mean cumulative seedling emergence (a) and mean seedling survival (b) per quadrat (0.04 m^2) for five treatments over 24 months.

Changes with time in total seedling survival percentage were similar for all treatments with approximately 50% seedlings surviving by the end of experiment (Fig. 2.13). However, the herbivore-protected plots initially appeared to favour survival but then showed a steady reduction in percentages of seedling survival with time (mainly over summer). Competition from grass alone was apparently not enough to suppress seedlings in comparison with effects from the herbivory (Treatments 2 and 4) with the speed of reduction in seedling numbers from June 2008 to January 2009 faster for these treatments. This trend was different from intact vegetation treatment (Treatment 5) with an increase in the percentage of seedlings survived during this period (Fig. 2.13).

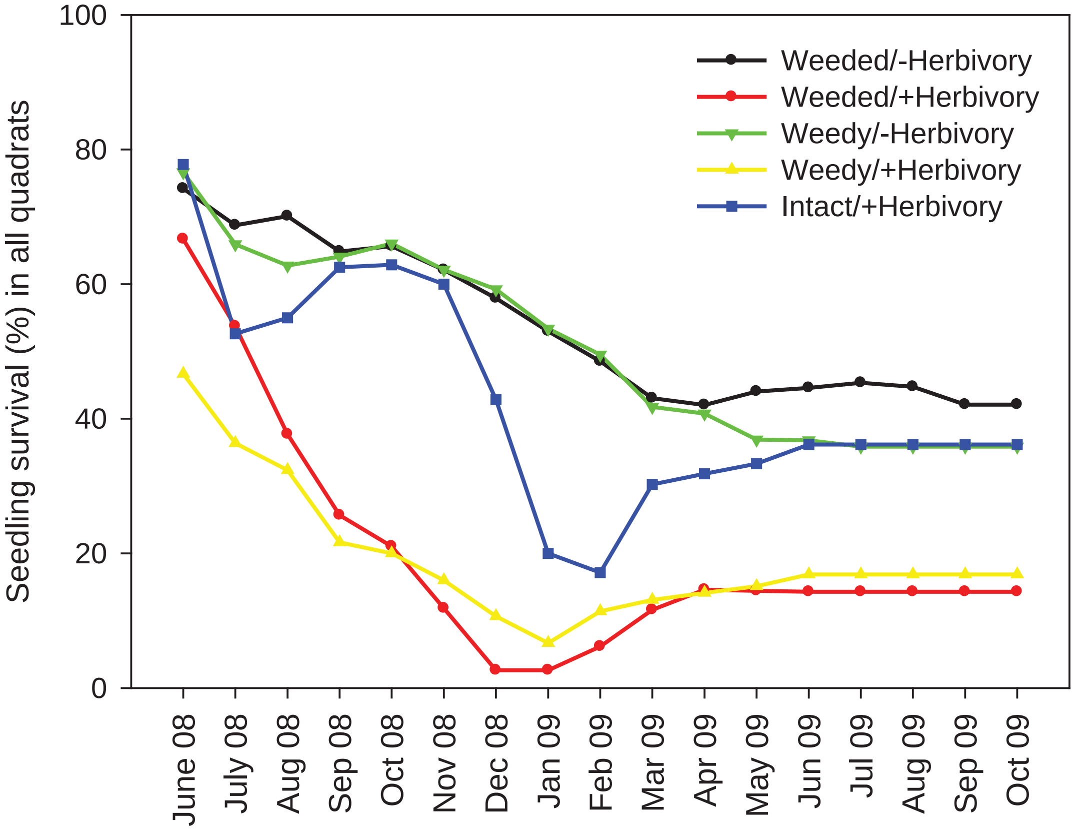


Figure 2.13. Seedling survival percentages in all quadrats (each 0.04 m^2) in each treatment over 17 months (data from June 2008 to October 2009 only).

2.4 Discussion

2.4.1 Broom seed bank and seed germination under **Pinus radiata** *stands*

The prolonged persistence of seed banks is a trait that is usually found in species that favour habitats where the environmental and/or disturbance regimes are unpredictable and thus the probability of seedling success is low or variable (Parker *et al.* 1989). There has been an increased awareness of and interest in the role that seed banks may play in influencing the colonisation and structure of plant communities (Roberts 1981; Fenner 1985; Leck *et al.* 1989; Bakker *et al.* 1996; Cabin & Marshall 2000; Thompson 2000). The dynamics of a seed bank involves a series of events. The input is determined by the seed rain. This way of dispersion includes passive forms, mechanical ejection of seeds, fire, wind, water and animals (Simpson *et al.* 1989). In addition, seed banks are highly variable in composition, lifetime, and functional significance (Adams *et al.* 2005). Seed banks have only recently begun to be incorporated in demographic models of plant populations. This is probably because seed bank data (e.g. seed survival and germination rates) are often more difficult to collect than data for adult plants (Adams *et al.* 2005). Models can provide inaccurate assessments if they fail to include important life stages such as seed banks (Doak *et al.* 2002).

Results for the broom seed bank measured in my study at the Tree Farm (0 to 16,901 seeds m^{-2} at 0–5 cm) shows a high variability among the three *P. radiata* stands at different depths but are comparable with the seed bank of broom in other studies (Smith & Harlen 1991; Allen *et al.* 1995; Hosking *et al.* 1996; Paynter *et al.* 1998; Downey 2000; Sheppard *et al.* 2000; Sheppard *et al.* 2002; Alexander & D'Antonio 2003a; Haubensak & Parker 2004; Wearne & Morgan 2006; Pauchard *et al.* 2008; Geerts *et al.* 2013) and to other invasive legume shrubs (Lonsdale *et al.* 1988; Gonzalez *et al.* 2009).

In this study, the highest seed density in the 0–10 cm was from the 9-year-old stand (approximately 4000 seeds m^{-2}) perhaps as the result of continuing seed rain from the dense mature broom present on the site. Seed rain of broom was found to range from 28 to 365 seeds m^{-2} at Barrington Tops (Australia) (Smith & Harlen 1991), 8000 seeds m^{-2} (Australia) (Hosking *et al.* 1998), ranging from 30 to 11,040 seeds m^{-2} over three years (1997–2000) at Krawarree, New South Wales (Australia) (Sheppard *et al.* 2002) and ranging from 59 to 21,416 seeds m^{-2} over four years (2004–2008) in Palmerston North and Lincoln (New Zealand) (Paynter *et al.* 2010). My results on seed density are comparable with other studies on broom seed banks in grassland (Allen *et al.* 1995) and in pasture (Sheppard *et al.* 2000; Sheppard *et al.* 2002). In one study, after 8–10 years, the seed density increased threefold (3036 seeds m^{-2}) and remained steady at 15 years old (18,524 seeds m^{-2}) (Sheppard *et al.* 2000) and peaked at approximately 21,000 seeds m^{-2} (Sheppard *et al.* 2002). In contrast, the low seed bank density in the 2-year-old stand in my study was probably due to the losses from seedling emergence and from forest management operations such as logging, windrowing, and herbicide spraying. Mechanical disturbance probably breaks seed dormancy and brings the seeds to the soil surface and this, combined with reduced competition from surrounding vegetation induces a pulse of seed germination from the seed bank. A comparable situation appears to occur in gorse (Gonzalez *et al.* 2009). My results also indicated that even at the end of a typical *P. radiata* rotation (30 years), a viable broom seed bank is still present at high densities at 0–10 cm (approximately 3200 seeds m^{-2}), showing a high persistence of soil seed bank which is similar with the work of Downey (2000). In other cases, researchers have noted a decrease in the number of seeds with age perhaps due to the decay and death of seeds in the soil (Alexander & D'Antonio 2003b). This does not appear to be the case in my study, though of course, more extensive sampling of different age stands would be needed to determine if, and when, viable seed bank densities peak during the pine harvest cycle. In the oldest *P. radiata* stand, the seeds have not been there for 30 years. They were probably produced by some scattered broom plants until quite recently (*personal observations*). Broom starts to die back naturally when tree stands are about 10 years old (Mike Watt, *personal communications*) but in this 30-year-old stand, broom plants were still present at the edge of the stand and continued producing some seeds to the soil seed bank.

High seed density is a characteristic of other broom genera such as French broom (*Genista monspessulana*) (510 to 3975 seeds m^{-2}) (Pauchard *et al.* 2008), Montpellier broom (*G. monspessulana*) (909 to 2727 seeds m^{-2}) and Spanish broom (*Spartium junceum*) (0 to 21,364 seeds m^{-2}) (Geerts *et al.* 2013). Such a large seed bank is likely to pose serious difficulties for forest managers trying to find options to control further broom invasions from seed bank. Allen *et al.* (1995) found that broom plants added a mean of 200 seeds m^{-2} by 4 years of ages so control methods should target broom plants under this age.

The results of my study showed high variability in seed density among the three stands, but multiple samples from within single stands does not constitute a robust test of age effects without many more stands being sampled to look for consistent stand age effects.

2.4.2 Effects of scarification and burial depth on broom seedling emergence

The high dormancy and longevity of broom seeds is a very important factor for finding suitable options for controlling this species. In the field, broom germination can be stimulated by soil or vegetation disturbance including commercial forestry operations, fire, cultivation, slashing, herbicide application, roadwork or animal digging (Partridge 1989; Zielke *et al.* 1992; Harrington 1993; Paynter *et al.* 1998; Robertson *et al.* 1999; Downey 2000; Paynter *et al.* 2003). A seed's position in the soil profile probably influences its likelihood of germination. In New Zealand, broom seed can generally be found in the top 5–6 cm of soil and occasionally as deep as 15 cm (Williams 1981; Partridge 1989), as seen in my study (see Section 2.4.1).

Results obtained from my laboratory study showed that all seeds used in the three treatments had a high viability (100%) with rapid germination rate and seeds scarified by machine for 20 seconds showed the highest germination percentage as a result of suitable conditions in the germinator and helped by having seeds treated with a fungicide. These results suggest that untreated broom seeds remain dormant due to an impervious seed coat. Results from this experiment therefore were used for designing the later experiment in this chapter and in Chapter 3 where seeds were sown into the field and in Chapter 4 when seeds sown into pots.

Results from the field seed sowing experiment indicated that seeds sown at different depths to 2 cm did not differ in emergence rate but effects of the scarification treatments were strongly significant. Overall, there were relatively low rates of field emergence (11–26%) across all treatments over the 18 months the experiment ran, and the scarification performed means the low emergence could not be because the seeds were dormant. This shows that germination success under field conditions depends on factors other than just than seed dormancy. Temperature and water supply are critical drivers for seed dormancy (initiation, break) and germination during plant regeneration (Walck *et al.* 2011). During the beginning of the experiment, seeds sown were watered daily to reduce seasonal effects (summer), then seeds that had been scarified geminated relatively soon. However, changes in soil moisture in hot summer at the site along with broken seed coats apparently caused many seeds to die. A factor affecting seed death might have been fungal activity because the seed coat was broken. The main mortality factors at the seed stage are seed ageing, seed predation and attack by bacterial and fungal microorganisms (Wagner & Mitschunas 2008). It is predicted that species with physical seed dormancy will rely on physical defences to exclude predators and pathogens, and rapid seed germination to escape pathogens at the emergence stage (Dalling *et al.* 2011). Broom germinates most successfully in sites exposed to direct solar radiation, with or without litter (McAlpine & Drake 2003). In my study, the unscarified seeds exposed to bare soil (simulating disturbance) would have been subject to changing cold/hot temperatures that presumably caused seed coats to break over time.

2.4.3 Effects of disturbance and herbivory on broom seedling emergence and survival

Disturbance, defined as a punctuated event that kills organisms or removes part of their biomass (D'antonio *et al.* 1999), has long been recognised as a major factor which may promote biological invasion (Elton 1958; Crawley 1987) by releasing both space and resources for establishment (Davis *et al.* 2000; Shea & Chesson 2002). Light and soil moisture profiles, soil nutrient content, and factors that modify the use of these resources such as air and soil temperature are affected by the extent of vegetation damage or removal (Collins *et al.* 1985; Runkle 1985). Invasive plant management strategies have included designed disturbance such as cultivation, burning, and herbicides that create or eliminate site availability (Sheley & Krueger-Mangold 2003). The availability of seeds and the availability of sites suitable for seedling establishment (safe sites; (Harper *et al.* 1961)) are key determinants of recruitment in plant populations (Harper *et al.* 1965; Crawley 1990; Eriksson & Ehrlén 1992). A common requirement for seedling recruitment is the absence of competition with other species within the immediate vicinity (Gurevitch *et al.* 2000). Moreover, the impact of seed losses on plant population size can be considered as a function of the density of safe sites (Andersen 1989).

The seed bank under broom plants in this *Eucalyptus* spp. plantation is relatively high (mean seed density was 2312 seeds m^{-2} for three depths; see Section 2.2.3 for details). The rate of seedling emergence from this seed bank was not different among all the combinations of treatments, indicating that disturbance (removal of grass) did not affect the outcome of seedling emergence. Even at a high density of grass cover (nearly 100% in the weedy, herbivory protected treatment), broom seedling emergence was relatively high by August 2008 (400 seedlings m^{-2}). Similarly, Sheppard *et al.* (2000) showed that soil cultivation did not alter germination rates of broom in three sites in Australia. Parker (2001) also found that disturbance did not promote broom seed establishment. However, in California, broom germination at one site increased when soil was disturbed (Bossard 1991). At another site in this study, quail and blue grouse preferentially foraged in disturbed areas, and the interaction of these seed predators and seed dispersers (ants) modified the abiotic effects of habitat disturbance on seedling establishment, resulting in no significant differences in seedling recruitment between disturbed and undisturbed sites (Bossard 1991). The variation in responses may be due to site factors (safe site) such as moisture conditions at the site at the time of treatment applications and competing vegetation, i.e. the removal of the surrounding vegetation could increase the levels of drought stress experienced by seedlings due to soil temperature variations resulting from direct sunlight and radiative cooling, increasing seedling mortality (Smith 2000; Parker 2001). Effects of disturbance on seedling establishment therefore are difficult to generalise from one population or habitat to another (Bossard 1991).

Seedling survival in my study was somewhat affected by herbivory (most probably by rabbits) but again was not affected by ground disturbance. Harrington (2007) recognised that herbivory from unknown sources appeared to be the primary cause of reductions in broom seedling abundance over time, especially in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) shelter-woods and thinned stands where leaves of broom seedlings were commonly browsed in the late summer and autumn, resulting in their subsequent mortality. Because, in general, seedlings and juvenile woody plants are particularly susceptible to herbivores (Grubb 1977) and broom plants, in particular, are well known to have varying palatability to herbivores (sheep) (Bellingham & Coomes 2003), the rate of herbivory can be extremely important in determining the rate of seedling survival in this species. The timing of herbivory in relation to phenological stage also appears to be a critical factor affecting both the survival and re-growth rates of *Genista scorpius* in Spain (Valderrábano & Torrano 2000).

Rabbit grazing has been shown to reduce seedling densities of woody species in Britain with the reduction being more pronounced with disturbance than without (Edwards & Crawley 1999). Moreover, interactions between soil disturbance, propagule availability and herbivory, rather than disturbance alone, plays an important role in controlling seedling recruitment (Edwards & Crawley 1999). Maron and Simms (1997) suggested that granivores exert strong but habitat-dependent effects on bush lupin *(Lupinus arboreus)* seed survival and seedling emergence. In my study, the effects of herbivores (probably rabbits) on seedling survival were noticeable, and many, quite well-established, older seedlings suffered grazing once exposed by the disturbance treatments and the protection from grazing in the intact plot may have compensated for reduced germination and emergence making the establishment rate similar to the disturbed plots.

In areas where water is a limiting factor, seedlings emerging in the spring cannot survive the summer without presence of vegetation cover (Harrington 2007). Drought was observed to be the overriding cause of broom seedling mortality, inflicting greater losses at sites with shallower or river sand-based soils (Sheppard *et al.* 2002). Harrington (2007) also found that drought may have been responsible for mortality of some broom seedlings, particularly in Douglas-fir thinned stands where wilted broom seedlings were observed in late summer. During the course of my study, broom seedling survival may have also been affected by the changing seasons and soil conditions as many young seedlings appeared to die when the soil became dry especially in the disturbed plots. The site was on the hillside that was facing mainly north, and northerly aspects are very prone to drying out in summer as they have the sun shining on them for much of the day.

In conclusion, the results from three studies in this chapter are useful in identifying some key aspects of broom ecology that drive the management of this species in which control options should target the broom seed bank and seedling stages in order to be successful. The next four chapters will explore such management options further.

CHAPTER 3
COMPETITIVE EFFECT OF SOWN GRASSES ON SUPPRESSION OF BROOM (*Cytisus scoparius*) SEEDLINGS

3.1 Introduction

Affordable, long-term methods of weed control are lacking for many of the world's most problematic exotic, invasive species (Perry *et al.* 2009). Herbicides or mechanical removal can provide a short-term control of invasive species, but are difficult and expensive to apply over large spatial scales, require reapplication for long-term control, and often do not promote establishment of desired vegetation (Sheley & Krueger-Mangold 2003). Planting a cover crop to compete with invasive species has been considered a potential approach for reducing invasive species success and increasing desired species success in ecological restoration and agriculture (Sheley & Larson 1994; Landhausser *et al.* 1996; Perry & Galatowitsch 2003; Singh *et al.* 2003; Ledgard & Davis 2004; Blackshaw *et al.* 2006; Sheley *et al.* 2006; Perry *et al.* 2009). Unfortunately, cover crops often fail to improve the desired species success, in part because they do not act selectively (Perry *et al.* 2009). Cover crops that are strong enough competitors to control the invasive species also tend to strongly suppress the desired species, whereas cover crops that do not strongly suppress the desired species also tend not to suppress the invasive species (Lanini *et al.* 1991; Hoffman *et al.* 1993; De Haan *et al.* 1994; Perry & Galatowitsch 2003; Ledgard & Davis 2004).

For cover crops to act selectively, they must create conditions that the desired species can tolerate better than the invasive species. For example, cover crops that reduce resource availability might favour the desired species over the invasive species when the desired species have lower resource requirements than the invasive species (Perry & Galatowitsch 2006). Shade may inhibit the invasive species more than the desired species when species such as invasive annuals are adapted to disturbed environments with high light availability (Bazzaz 1996) more than the desired species. Thus, planting a fast growing cover crop that can establish rapidly and produce abundant shade might be expected to favour some desired species over invasive species (Perry & Galatowitsch 2006), especially in disturbed areas with elevated light availability.

Broom seeds are dormant and can remain viable in the soil for many years so that after forest clearing, re-establishment from seed occurs readily when conditions are favourable for germination. The best method for removing broom without increasing its regeneration appears to be one that stimulates abundance of associated competing vegetation (Harrington 2011). As broom is generally shade intolerant (Peterson & Prasad 1998), over-sowing with grasses and legumes as cover crops seems to be a potential option for controlling this species. The logic of over-sowing is to establish a cover crop so that the crop trees and cover crops are mutually supportive rather than competing with one another (Gous 1996b). The practice of herbicides followed by oversowing of grasses on controlling weeds like broom during early stage of forest establishment has been an option for many forests in New Zealand (Richardson 1993) but successful stories have not been reported. In some trials, a mixture of 10 kg Yorkshire fog (*Holcus lanatus* L.) ha^{-1} and 5 kg lotus (*Lotus uliginosus* Schk.) ha^{-1} was oversown in auntum (April) or a mixture of 10 kg annual ryegrass (*Lolium multiflorum* L.) ha^{-1}, 3 kg lotus (*L. uliginosus*) ha^{-1}, 1.5 kg browntop (*Agrostis capillaris* L.) ha^{-1} and 1.5 kg cocksfoot (*Dactylis glomerata* L.) ha^{-1} in spring (October) (Richardson *et al.* 1996a) but the competition effects of these grasses on broom were not clearly indicated. Species are normally mixed at higher sowing rates and sown at different seasons. These make it difficult to assess the effectiveness of each of the species on controlling broom seedlings since the cost of sowing is relatively high to forest managers (*personal communications*).

Gorse (*Ulex europaeus* L.), a leguminous, prolific weed of forestry and pasture in New Zealand, has become the focus of several studies testing the use of pasture grasses both alone or in combination with other control options (grazing and fertilizers) to control gorse seedlings (Thompson 1974; Hartley & Thai 1979; Ivens 1979; Ivens & Mlowe 1980; Hartley & Thai 1982; Popay *et al.* 1990).

Thompson (1974) evaluated the effects of two different pasture species, perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*), on competing gorse growth and establishment. These pasture species were sown in separate trials with different rates for perennial ryegrass (5, 10, 20 and 40 kg ha^{-1}) and white clover (1, 2, 4 and 8 kg ha^{-1}). After one year, white clover had much more severe competitive effects through the spring and summer although it caused only half the gorse mortality of ryegrass during the winter (Thompson 1974).

Hartley and Thai (1979) assessed the survival of gorse seedlings sown with Yorkshire fog (*H. lanatus*; 10 kg ha^{-1}), Italian ryegrass (*L. multiflorum*; 10 kg ha^{-1}), browntop (*A. capillaris*; 3 kg ha^{-1}), perennial ryegrass (*L. perenne*; 20 kg ha^{-1}) and white clover (*T. repens*; 3 kg ha^{-1}) under three grazing management schemes with/without fertiliser (nitrogen at 50 kg ha^{-1}). After one year, the survival of gorse seedlings was highest in a perennial ryegrass sward, lowest in browntop, with Yorkshire fog having an intermediate effect. Gorse seedling survival was reduced by the addition of white clover to the sward (Thompson 1974; Hartley & Thai 1979) but increased by Italian ryegrass (Hartley & Thai 1979). Lime reduced gorse seedling survival over winter while nitrogen had little effect (Hartley & Thai 1979).

Hartley and Thai (1982) used the same species and sowing rates as in Hartley and Thai (1979) to examine the survival of gorse seedlings sown with perennial ryegrass, Yorkshire fog, browntop, and white clover under three grazing management schemes with/without fertiliser (phosphate at 40 kg ha^{-1} and nitrogen at 50 kg ha^{-1}). After nine months, gorse survival was significantly lower under browntop than under perennial ryegrass with Yorkshire fog intermediate. Gorse seedling survival was reduced by the addition of white clover, phosphate, and nitrogen. Increased seeding rates of perennial ryegrass did not help gorse control but Yorkshire fog and browntop appeared better at controlling gorse at higher rates (Hartley & Thai 1982).

Popay *et al.* (1990) recognised the importance of fertiliser and lime on suppression of gorse seedlings. They extended the research of Hartley and Thai (1982) by using the same sowing rates for perennial ryegrass, Yorkshire fog and white clover with a higher rate for browntop (5 kg ha^{-1}) and added cocksfoot (*D. glomerata*; 10 kg ha^{-1}). The same amount of fertiliser was added under three grazing management schemes. After three years, gorse seedling numbers were reduced in treatments with lime, phosphate, and nitrogen with the effects of nitrogen apparently lasting longest. Different oversown pasture species had no effect on establishment or survival of gorse seedlings.

This work on gorse in pastures shows that to get better control on gorse seedlings, an integrated management approach is required. In a forestry context, however, it is hard to apply this approach because the success of using these ground covers is based on suitable scheduling of cover crop sowing, tree planting and weed seed germination (Potter & Kriticos 2007) along with the understanding of factors influencing both the ground covers and the controlled weeds. However, there is not much information on the effect of competition from grasses on broom establishment. In fact, Hosking *et al.* (1998) reported that broom seedlings died in plots where vegetation cover was < 20%, and that at sites near the climatic limit of the species in Australia, broom seedlings required grass species to help them establish. Because broom is capable of germinating at relatively low temperatures (Bossard 1993; Harrington 2009), the practice of seeding of perennial grasses in autumn, as soon as possible after a prescribed fire, is likely to ensure their establishment at the same time or earlier than emergence of broom seedlings.

This chapter summarises the results from a study carried out to: (1) compare the suppression of different ground cover species sown at different times of the year on broom seedling emergence, survival, and growth; and (2) identify factors affecting the success of ground covers in out-competing broom seedlings.

3.2 Materials and methods

3.2.1 Study site

Two separate experiments were conducted in a pasture (40°23'S, 175°36'E) with no previous history of broom populations at the Moginie Pasture and Crop Research Unit of Massey University, Palmerston North, New Zealand from May 2008 to May 2009 (Autumn Experiment) and from November 2008 to November 2009 (Spring Experiment). Average monthly temperature and rainfall during the time of the experiment (collected by the Grasslands AgResearch weather station approximately 1 km away from the study site) are shown in Fig. 3.1. The maximum daily temperature ranged from 22.6°C in January to 11.8°C in June.

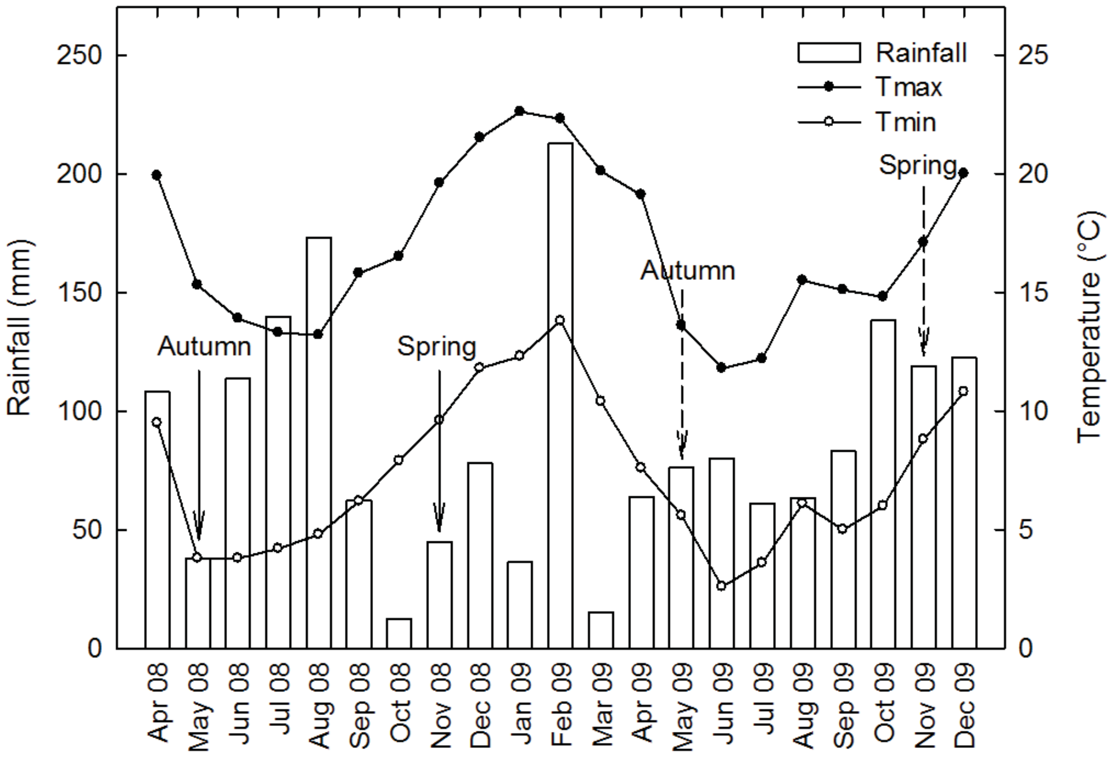


Figure 3.1. Mean monthly rainfall (mm) and mean monthly maximum (Tmax) and minimum (Tmin) temperature (°C) over the course of the two ground cover seed-sowing experiments. The solid arrows show the time when the sowing experiments were applied in autumn (12 May 2008) and spring (3 November 2008) and the dashed arrows indicate the date of termination of the experiments (after one year).

The soil was a Tokomaru silt loam and samples taken from the trial site had an average pH of 5.2. Olsen-P was measured at 43 μg mL^{-1} and the Na, Mg, K and Ca levels averaged 0.16, 0.74, 0.77 and 3.2 me 100g^{-1}, respectively. Soil organic matter averaged 5.3% and average CEC of 13 me 100 g^{-1}.

3.2.2 Seed collection and preparation

Broom

Broom seeds were collected from soil on 8 August 2008 from beneath a mature broom plant in a *Eucalyptus* spp. plantation at the Veterinary Large Animal Teaching Unit, Massey University (40°23'S, 175°37'E). The seeds extracted from the soil were laid out on filter paper overnight to dry and then stored in paper bags at 5°C. The seeds were scarified just before sowing using a Forsberg scarifier for 20 seconds as this duration of scarification gave the highest rate of germination from a laboratory experiment (Chapter 2). Scarified seeds were then treated with thiram wet powder (800 g a.i. kg^{-1} as Thiram 80) to prevent fungal attack.

Grass species

Before deploying in the field experiments, the viability of seed lots of Yorkshire fog, Italian ryegrass and perennial ryegrass seeds were tested for germinability in the laboratory on 7 April 2008 (before the Autumn Experiment) and again on 1 October 2008 (before the Spring Experiment). One seed from each species was separately placed on each cell of a 25-grid filter paper in a plastic box (17 cm × 12 cm wide and 5 cm deep) (25 seeds per box × 4 replicates). The boxes were dampened with water and placed in an incubation chamber that maintained 16 hours light at 30°C and 8 hours darkness at 20°C as suggested by the International Seed Testing Association (Don 2006). Distilled water was added regularly to the seeds as needed. Seed germination was monitored over 28 days and the number of seeds germinated was assessed, counted and removed weekly. Results obtained at the end of germination tests (after 28 days) are shown in Table 3.1. These figures were then used to adjust the actual sowing rates used for each species in each experiment.

Table 3.1. Results of the laboratory germination tests for grasses before the Autumn and Spring Experiments. Dates shown here are final readings (after 28 days).

Date	*Species*	*Germinability (%)*
5 May 2008	Yorkshire fog	93
(before Autumn Experiment)	Italian ryegrass	95
	Perennial ryegrass	94
29 October 2008	Yorkshire fog	88
(before Spring Experiment)		
	Italian ryegrass	93
	Perennial ryegrass	89

3.2.3 Broom field experiments

Two seed-sowing experiments were conducted, one in autumn and one in spring. The experiments were a randomised block design in which the site was divided into two parcels of land, corresponding with two different times of establishment (sowing season, autumn and spring), and treated as blocking factors (Figs. 3.2 and 3.3). There were four blocks (replicates) for each of the two experiments (time of establishment). Ground cover species with varying sowing rate were randomly assigned within each plot.

The existing vegetation was cleared before the experiment, using glyphosate (Roundup Transorb at 7 ml L^{-1}) to kill all species present followed two weeks later by cultivation to form a suitable seedbed. The area was then divided into four replicate blocks, each was 48 m^2 (6 × 8 m) with spacing between each block of 0.5 m (Fig. 3.2). Thus each block had 12 plots sized 4 m^2 (2 × 2 m) representing treatments of three types of ground covers with three sowing rates and a control treatment, in which broom seeds sown without ground covers, were randomly assigned inside each plot (Fig. 3.2). Strips of grasses between the blocks were kept intact to prevent edge effects. In each block, grass swards were sown just prior to sowing scarified broom seeds. The grass seeds were weighed for each pegged out plot, scattered by hand and raked in. No irrigation was applied to simulate what might happen if this was a forestry site.

Three ground cover species (Yorkshire fog, Italian ryegrass and perennial ryegrass) and three sowing rates (half rate, standard rate and double rate) were used (Table 3.2). The sowing rates of grass species recommended to apply in *P. radiata* forest sites during establishment were: Yorkshire fog (2 kg seed ha^{-1}), Italian ryegrass (10 kg seed ha^{-1}) and perennial ryegrass (10 kg seed ha^{-1}) (Robert Coulson, *personal communication*). In addition, two extra plots, one of Italian ryegrass and the other of Yorkshire fog, were sown at standard rates and broom seeds and set aside to be sown into after 6 months once the grasses were well established (Fig. 3.2). One plot with broom seeds sown without ground covers sown was used as a control treatment. Each treatment was replicated four times so the total number of treated plots for each experiment was 48.

In each plot, 44 broom seeds were sown evenly in the centre at spacing 15 × 15 cm using a 49-grid aluminium frame with wires (Fig. 3.2d). Sowing of the first experimental block of land (the Autumn Experiment) was started on 12 May 2008, of which each block was finished within one day, i.e. each day was used as a blocking factor (Block 1 (12 May 2008), Block 2 (13 May 2008), Block 3 (15 May 2008) and Block 4 (16 May 2008), respectively). In addition, an extra plot of both Italian ryegrass and Yorkshire fog was sown in each block in May at standard rates and broom seeds were sown into them on 15 November 2008 once the grasses had been present for six months. Sowing of the second experimental block of land (the Spring Experiment) was started on 3 November 2008, and again each block was finished within one day as follows: Block 1 (3 November 2008), Block 2 (4 November 2008), Block 3 (8 November 2008) and Block 4 (9 November 2008). Once again, two extra plots of Italian ryegrass (I10A) and Yorkshire fog (Y2A) in each block were sown in November at standard rates and broom seeds were sown into them on 14 May 2009 once the grasses had been present for six months.

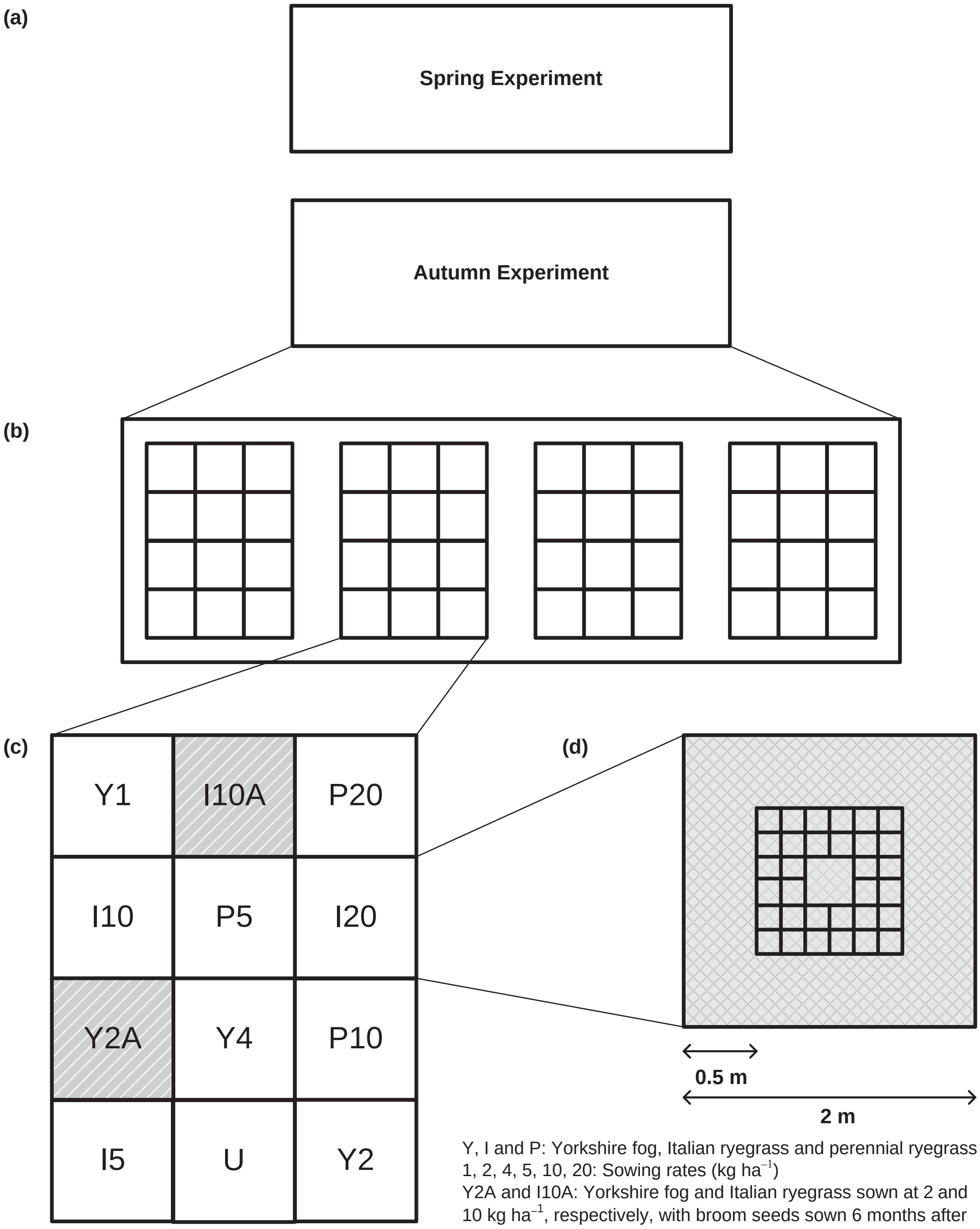


Figure 3.2. Layout of the trials. (a) The two spring and autumn experiments. (b) Layout of a randomised block design with four blocks. (c) A sample block with 11 sowing density treatment plots and an unsown plot as a control treatment (two extra grey dash plots of Italian ryegrass and Yorkshire fog sown at standard rates and broom seeds were sown into them once the grasses were established). (d) A sample plot with 44 broom seeds sown regularly in the centre along with a certain type of ground cover.

Figure 3.3. A picture showing experimental plots (Autumn Experiment).

Table 3.2. Treatments of grass species and sowing rates applied in the two experiments.

No.	*Grass species*	*Sowing rate (kg ha^{-1})*	*Code*	*Note*
1	Yorkshire fog	1	Y1	
2	Yorkshire fog	2	Y2	Standard rate in forestry
3	Yorkshire fog	4	Y4	
4	Italian ryegrass	5	I5	
5	Italian ryegrass	10	I10	Standard rate in forestry
6	Italian ryegrass	20	I20	
7	Perennial ryegrass	5	P5	
8	Perennial ryegrass	10	P10	Standard rate in forestry
9	Perennial ryegrass	20	P20	
10	Untreated control	NA	U	
11	Yorkshire fog	2	Y2A	Broom sown after six months
12	Italian ryegrass	10	I10A	Broom sown after six months

3.2.4 Data collection and harvesting

Data collection

The number of broom seedlings that emerged and their fate (survived or died) in each plot was recorded monthly over the first three months after the sowing of grasses and then monitored at 3-monthly intervals thereafter. The relative sizes (heights and diameters at the base) of broom seedlings and/or plants were measured. These measurements were compared among different ground cover species and with the time of sowing. The botanical composition of sown ground covers and volunteer grasses and weeds surrounding broom plants within each plot was scored as height and percentage cover of each species. Each experiment ran for 12 months and broom and botanical composition were harvested at the end of each trial.

Harvesting of broom and botanical composition

At the end of the study (one year) for each sowing season, all broom plants and samples of ground covers present in each plot (Treatments 1 to 10) were harvested to assess the percent dry matter (DM, %) and dry weight (kg ha^{-1}). Data on broom and botanical composition were recorded on the day of harvesting using the same approach mentioned above.

All broom plants in each plot were cut near ground level, kept in a plastic bag, and subsequently transported to the lab for measuring the total fresh weight for each bundle of broom. A representative sample was taken from each bundle in order to assess their biomass. The sample was then put through a mulcher to create fine materials, measured as fresh weight and then dried in an oven at 80°C to a constant weight for assessing the percent dry matter and the dry weight (kg ha^{-1}) for each treatment.

For botanical composition, three representative quadrats sized 50 × 20 cm were randomly located in each plot and three samples of foliage materials cut at about 3–5 mm from soil level using a battery-powered grass shear. These three samples then were stored in a plastic bag, transferred to the lab to measure the fresh weights of these samples. After thoroughly mixing the materials from the bag, two sub-samples were taken. For one sample, the fresh weight was weighted, dried in an oven over night and then weighed again. The percent DM of this sub-sample was calculated and the DM extrapolated for the whole plot. For the other sub-sample, individual components of species were separated. Each lot of material was oven dried at 80°C to a constant weight then dry weights were recorded. The dry weight (kg ha^{-1}) of each component for the plot was calculated.

3.2.5 Data analysis

All statistical analyses were conducted using SAS 9.2 software (SAS Institute Inc. 2008). Treatment effects were considered significant at $P < 0.05$ for all analyses.

3.2.5.1 Broom seedling emergence and survival

Data on broom seedling emergence and survival in each plot at the end of the experiment (after one year) were used for analyses. Preliminary analyses of residuals were performed on the proportion of seedlings that emerged from the number of seeds sown at the beginning (44 seeds per treatment) and on the proportion of seedlings that survived (only for seedlings that emerged) using PROC UNIVARIATE. These revealed a skewed error distribution and so generalized linear mixed models were fitted to the seedling emergence and the seedling survival data using PROC GLIMMIX (Willenborg *et al.* 2005; Harrison *et al.* 2007; Fedriani & Delibes 2009) with binomial error terms (O'Hara & Kotze 2010).

The data from the two experiments were combined for analyses using a split-split-plot model: sowing season was the whole plot factor, sowing species the split-plot factor, and sowing rate the split-split-plot factor. The "sowing season", "sowing species" and "sowing rate" and their interaction were treated as fixed effects and the block, block × sowing species × sowing rate treated and block nested in sowing season as random effects (Littell *et al.* 2006). Adjusted means and standard errors were calculated using LSMEANS and back-transformed using ILINK option with the inverse link function to the estimate on the linear scale (Littell *et al.* 2006). To compare the effects of different levels of any significant main factor, the differences between their least square means were calculated. When the interaction between any two factors and/or three factors was significant, tests for the effect of a given factor at the different levels of the other factor (''tests of simple main effects'') were performed using SLICEDIFF option in LSMEANS of GLIMMIX procedure (Littell *et al.* 2006).

3.2.5.2 Percentage cover

Data on percentage cover of sown grasses and other volunteer grasses and weeds collected after 3-month intervals were analysed separately for each experiment with a linear mixed model repeated measures analysis of variance (ANOVA) using PROC MIXED with the restricted maximum likelihood estimation method. The "sowing species", "sowing rate" and their interaction were treated as fixed effects, time of sampling was the repeated measure and the block and block × sowing species × sowing rate treated as random effects. Assumption of normality of residuals was checked by PROC UNIVARIATE and since the preliminary results were not normally distributed, the percent cover data were arcsine, square-root transformed before being analysed to stabilise the variance. Tukey's honestly significant difference (HSD) tests were then used to perform multiple comparisons between all pairs of treatments when ANOVA results indicated significant treatment effects.

3.2.5.3 Dry matter production

Data on dry matter (DM, kg ha^{-1}) production of broom, sown grasses and botanical composition at the end of the experiment from the two experiments was combined for analyses with a linear mixed model ANOVA using PROC MIXED with the restricted maximum likelihood estimation method. The statistical model accounted for the split-split-plot design: sowing season was the whole plot factor, sowing species the split-plot factor, and sowing rate the split-split-plot factor with "sowing season", "sowing species" and "sowing rate" and their interaction were treated as fixed effects and the block, block × sowing species × sowing rate treated and block nested in sowing season as random effects (Littell *et al.* 2006). Assumption of normality of residuals was checked by PROC UNIVARIATE and since the preliminary results were not normally distributed (except for broom dry weight data) the dry matter data were $\log(x+0.5)$ transformed before being analysed to stabilised the variance (Yamamura 1999). Tukey's honestly significant difference (HSD) tests were then used to perform multiple comparisons between all pairs of treatments when ANOVA results indicated significant treatment effects.

3.3 Results

3.3.1 Broom seedling emergence, survival and growth

Broom cumulative seedling emergence in each plot started soon within one month after sowing in the Autumn Experiment with the number of seedlings m^{-2} ranging from 6 (14.2% seeds emerged, Italian ryegrass sown at 20 kg ha^{-1}) to 10 (22.7% seeds emerged, Italian ryegrass sown at 10 kg ha^{-1}) in May 2008. There was a large increase by September 2008 when the number of seedlings m^{-2} ranged from 30 (69.9% seeds emerged, Italian ryegrass sown at 20 kg ha^{-1}) to 36 (81.3% seeds emerged, Yorkshire fog sown at 1 kg ha^{-1}) but did not increase further throughout the rest of the experiment (Fig. 3.4a). By contrast, seedling emergence in the Spring Experiment started more slowly with the number of seedlings m^{-2} ranging from 14 (31.8% seeds emerged, perennial ryegrass sown at 20 kg ha^{-1}) to 18 (42% seeds emerged, perennial ryegrass sown at 10 kg ha^{-1}) in January 2009 (two months after sowing) and then virtually ceased (Fig. 3.5a). At the end of the two experiments, the cumulative seedling emergence was significantly different between the two sowing seasons but was not significantly affected by sowing species nor sowing rate (Table 3.3).

There was a significant change in the number of surviving seedlings m^{-2} in each plot in the Autumn Experiment from January 2009, ranging from 17 (48.1% seedings survived, Yorkshire fog sown at 1 kg ha^{-1}) to 22 (63.3% seedings survived, perennial ryegrass sown at 5 kg ha^{-1}), which slightly decreased by the end of the experiment (Fig. 3.4b). By contrast, seedlings emerging from January 2009 in the Spring Experiment survived better throughout the course of the experiment with the number of surviving seedlings m^{-2} ranged from 13 (85.5% seedings survived, Yorkshire fog sown at 4 kg ha^{-1}) to 18 (94.4% seedings survived, Italian ryegrass sown at 5 kg ha^{-1}) in November 2009 (Fig. 3.5b). The survival of broom seedlings was also significantly different in the two sowing seasons and differed also by sowing rate but not on sowing species (Figs 3.4b and 3.5b; Table 3.3).

Importantly, there were no signs of broom seedlings emerging from plots sown into Yorkshire fog at 2 kg ha^{-1} (Y2A) and Italian ryegrass at 10 kg ha^{-1} (I10A) six months after grasses have already established in both sowing seasons.

The growth (height) of broom plants in comparison with that of grasses was relatively similar between the two experiments and among the treatments (Figs. 3.6 and 3.7). At the beginning, broom seedlings grew more slowly than grasses but after several months the broom plants appeared to easily out-compete the grasses and their height was soon more than double that of the grasses (Figs. 3.6 and 3.7). Interestingly, some of broom plants in the Spring Experiment started flowering and set seed pods by the end of the experiment 12 months later in November 2009 (Fig. 3.8).

Table 3.3. Effects of sowing season, sowing species and sowing rate and their interactions on mean cumulative seedling emergence and seedling survival per plot. Bold values indicate statistically significant effects at $P < 0.05$.

Effect	*Seedling emergence*		*Seedling survival*	
	F^1	*P*	*F*	*P*
Sowing season (SE)	$14.05_{(1,5.94)}$	**0.0097**	$121.37_{(1,72)}$	**<0.0001**
Sowing species (SP)	$0.15_{(2,72)}$	0.8610	$0.38_{(2,72)}$	0.6841
SE × SP	$1.68_{(2,72)}$	0.1937	$0.20_{(2,72)}$	0.8185
Sowing rate (SR)	$3.08_{(3,10.46)}$	0.0750	$4.62_{(3,59.16)}$	**0.0057**
SE × SR	$0.63_{(3,10.46)}$	0.6128	$1.69_{(3,59.16)}$	0.1783
SP × SR	$0.24_{(6,72)}$	0.9606	$0.58_{(6,72)}$	0.7467
SE × SP × SR	$0.58_{(6,72)}$	0.7457	$0.21_{(6,72)}$	0.9732

[1]Note: F test with degrees of freedom in the brackets

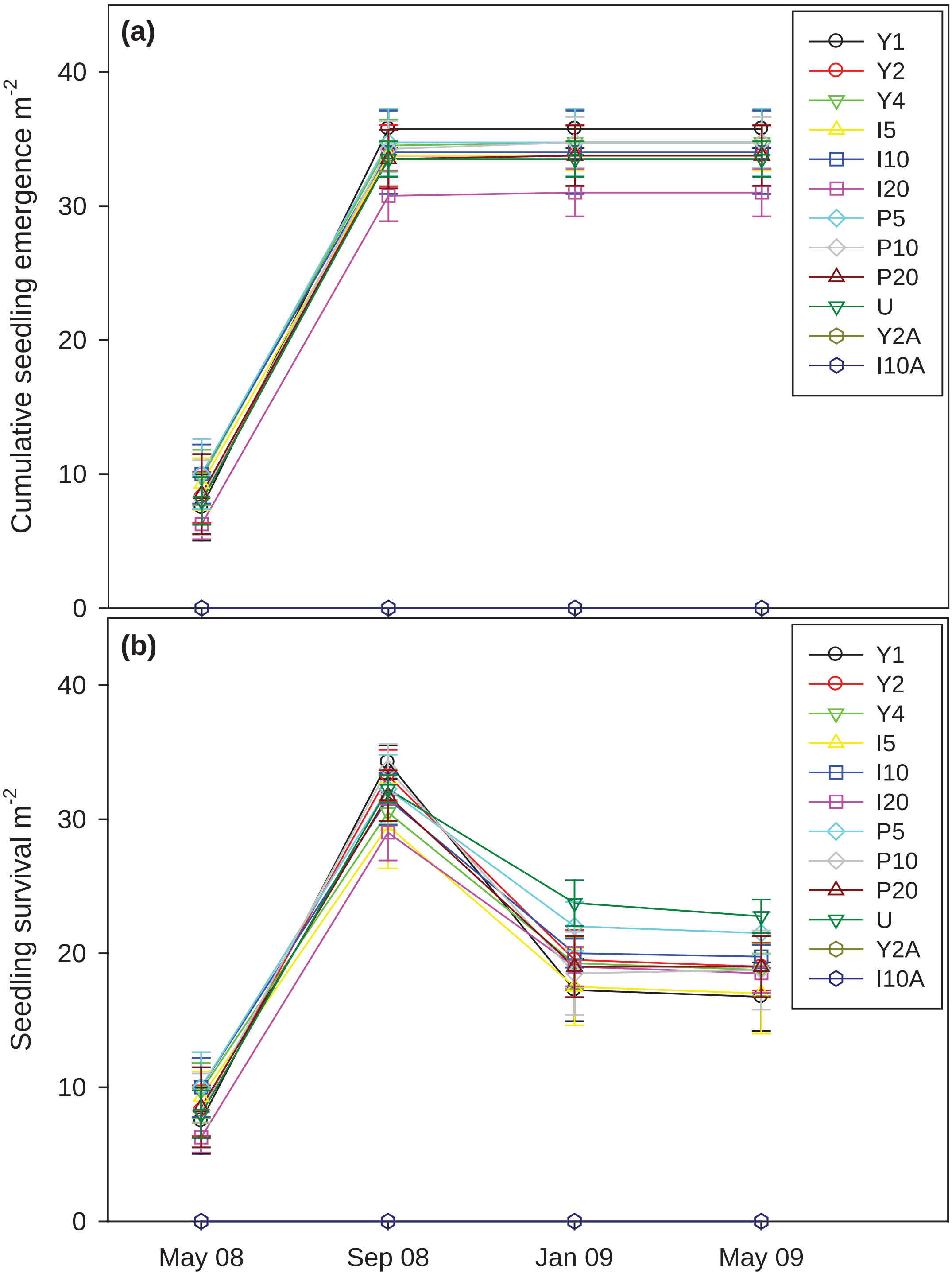


Figure 3.4. Mean (with ±1 standard error of the mean) m^{-2} of (a) cumulative seedling emergence and (b) seedling survival of broom in the Autumn Experiment over time. Y1, Y2 and Y4 were Yorkshire fog sown at 1, 2 and 4 kg ha^{-1}; I5, I10 and I20 were Italian ryegrass sown at 5, 10 and 20 kg ha^{-1}; P5, P10 and P20 were perennial ryegrass sown at 5, 10 and 20 kg ha^{-1} and U was untreated control treatment.

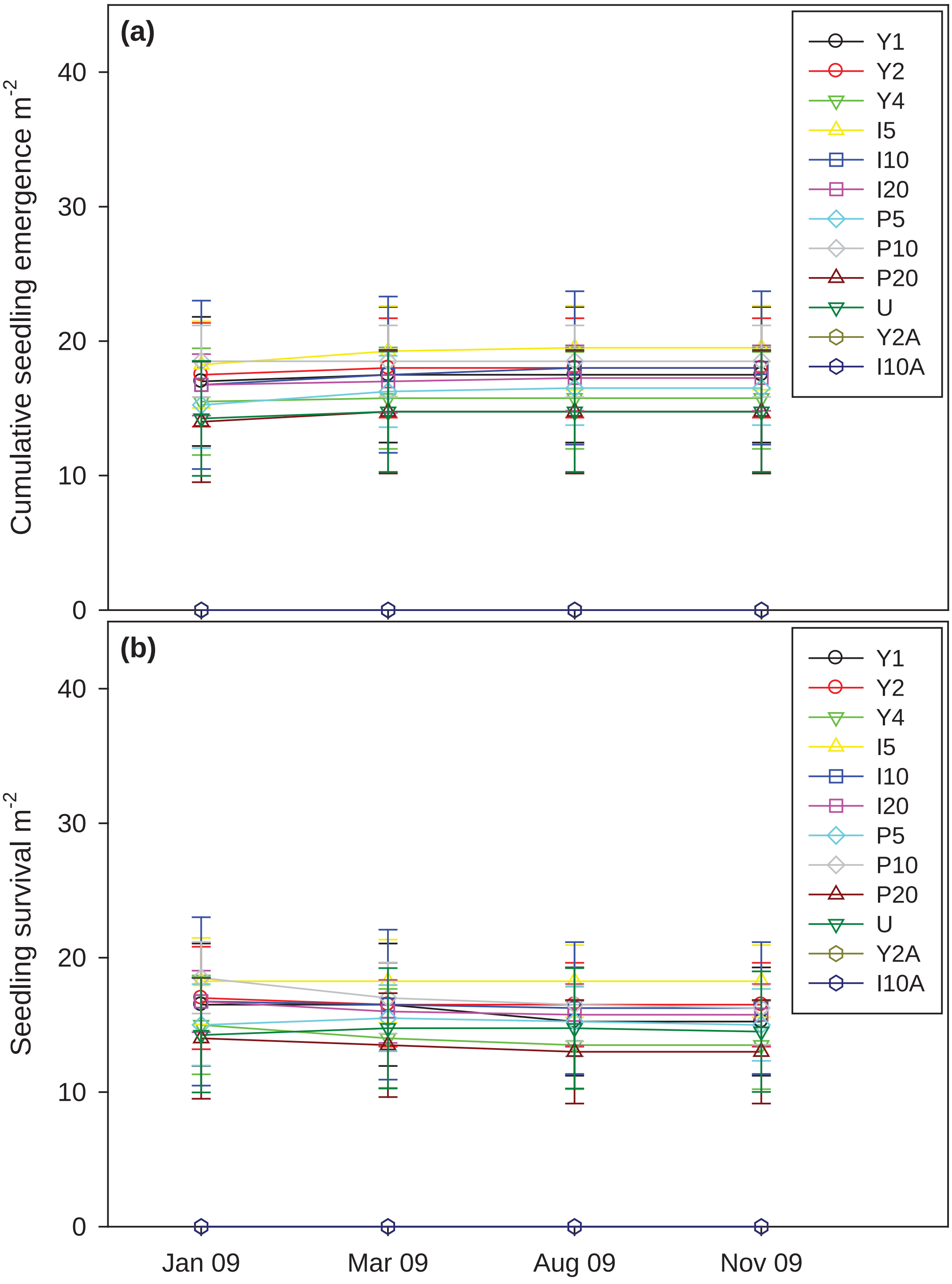


Figure 3.5. Mean (with ±1 standard error of the mean) m^{-2} of (a) cumulative seedling emergence and (b) seedling survival of broom in the Spring Experiment over time. Y1, Y2 and Y4 were Yorkshire fog sown at 1, 2 and 4 kg ha^{-1}; I5, I10 and I20 were Italian ryegrass sown at 5, 10 and 20 kg ha^{-1}; P5, P10 and P20 were perennial ryegrass sown at 5, 10 and 20 kg ha^{-1} and U was untreated control treatment.

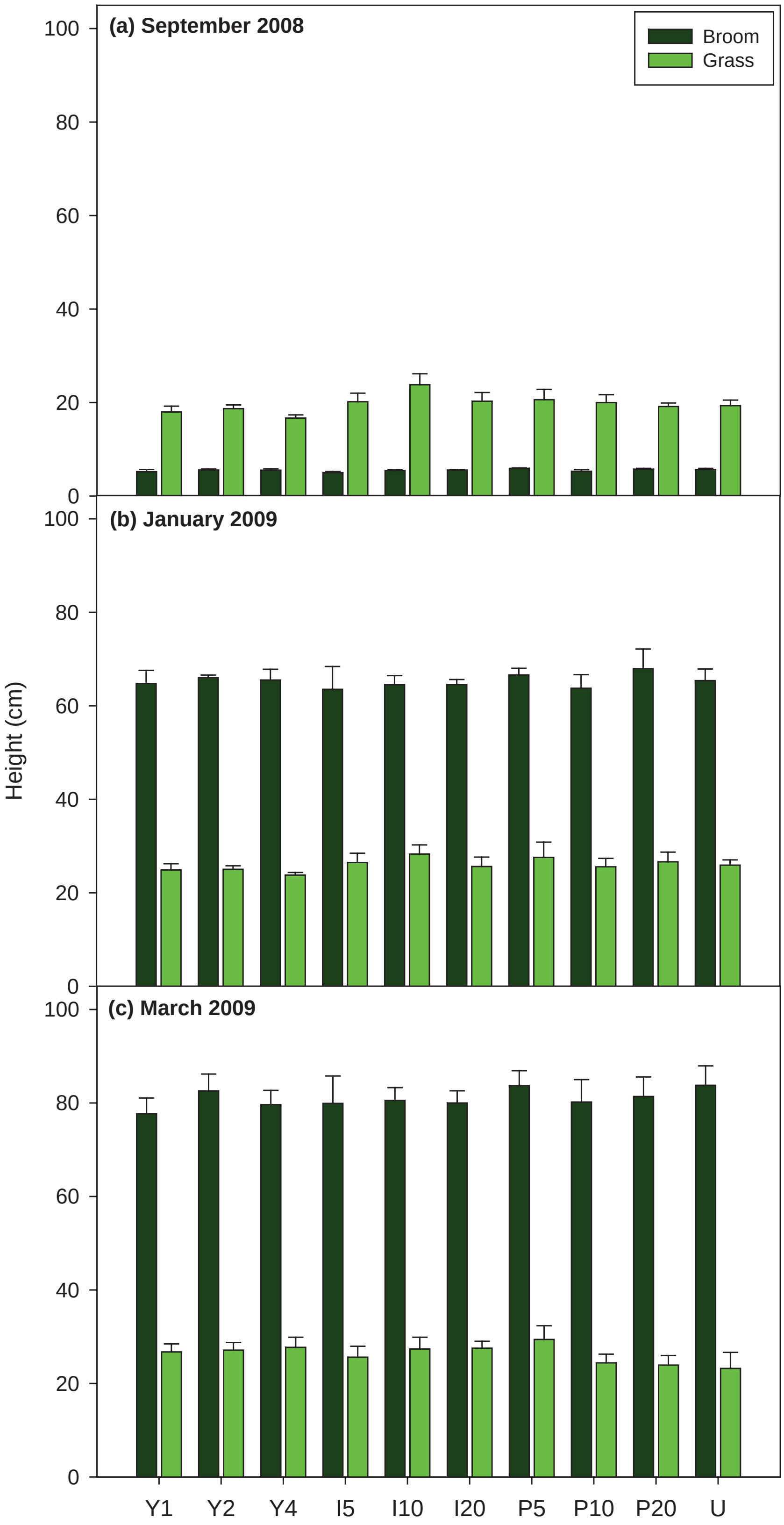


Figure 3.6. Mean height (with one standard error of the mean) of broom and grasses in the Autumn Experiment.

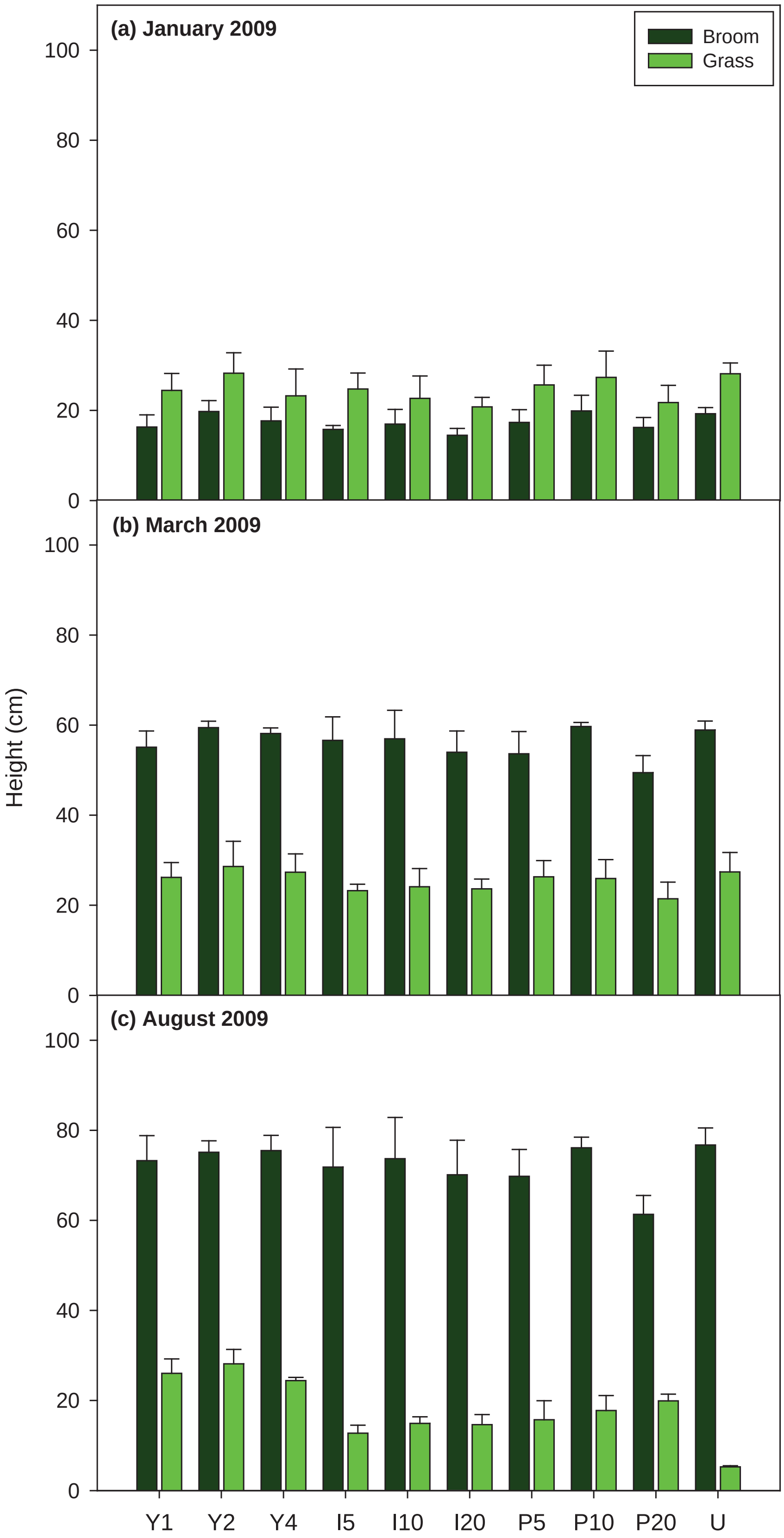


Figure 3.7. Mean height (with one standard error of the mean) of broom and grasses in the Spring Experiment.

Figure 3.8. A broom plant started flowering and producing seed pods in the Spring Experiment (5 November 2009).

3.3.2 Botanical composition

Over the course of the study, there was a relatively high turnover in the botanical composition of swards in the two experiments (Figs 3.9 and 3.10). Species present in the Autumn Experiment consisted of twin cress (*Lepidium didymium* L.), annual poa (*Poa annua* L.), toad rush (*Juncus bufonius*), broad-leaved dock (*Rumex obtusifolius* L.), chickweed (*Stellaria media* L. (Vill)), shepherd's purse (*Capsella bursa-pastoris*), prickly sow thistle (*Sonchus asper*), Scotch thistle (*Cirsium vulgare*), white clover (*T. repens*). Among these, white clover became dominant in all treatments with a relatively high percentage cover six months after the experiment began (Fig. 3.9).

Species present in the Spring Experiment included black nightshade (*Solanum nigrum*), broad-leaved dock (*R. obtusifolius*), white clover (*T. repens*), hawksbeard (*Crepis capillaris (L.)* Wallr.), hawkbit (*Leontodon taraxacoides* Vill. Merat), dandelion

(*Taraxacum officinale* Weber), creeping buttercup (*Ranunculus repens* L.), narrow-leaved plantain (*Plantago lanceolata*), nodding thistle (*Carduus nutans* L.), Scotch thistle (*C. vulgare*). Among these, black nightshade dominated three months after the experiment started but then subsequently was replaced by white clover and broad-leaved dock six months after the experiment began (Fig. 3.10).

There were significant effects of sowing species, sowing rate and their interaction on mean percentage cover of sown grasses (Table 3.4) but the magnitude was different between the experiments. The percentage cover of sown grass species in the Autumn Experiment increased from nearly 70% (Italian ryegrass at 5 kg ha^{-1} and perennial ryegrass at 10 kg ha^{-1}) to 90% (Yorkshire fog at 4 kg ha^{-1}) 4 months after sowing (September 2008) but then decreased to approximately 40% (Italian ryegrass at 5 kg ha^{-1}) by March 2009 as a result of an increasing percentage cover from volunteer grasses and other weeds (Fig. 3.9). During this time, a number of broom seedlings died perhaps as the result of combined effects from sown grasses and volunteer grasses (Fig. 3.4). By contrast, the percentage cover of sown grass species in the Spring Experiment slightly increased from 5% (Italian ryegrass at 5 kg ha^{-1}) to nearly 40% (Yorkshire fog at 4 kg ha^{-1}) 2 months after sowing (January 2009) and then steadily increased depending on sowing species and sowing rate. Yorkshire fog performed better (approximately 95%) at rates of 2 and 4 kg ha^{-1} seven months after sowing (August 2009) (Fig. 3.10). However, there was no difference between the treatments in number of broom seedlings surviving during this time (Fig. 3.5).

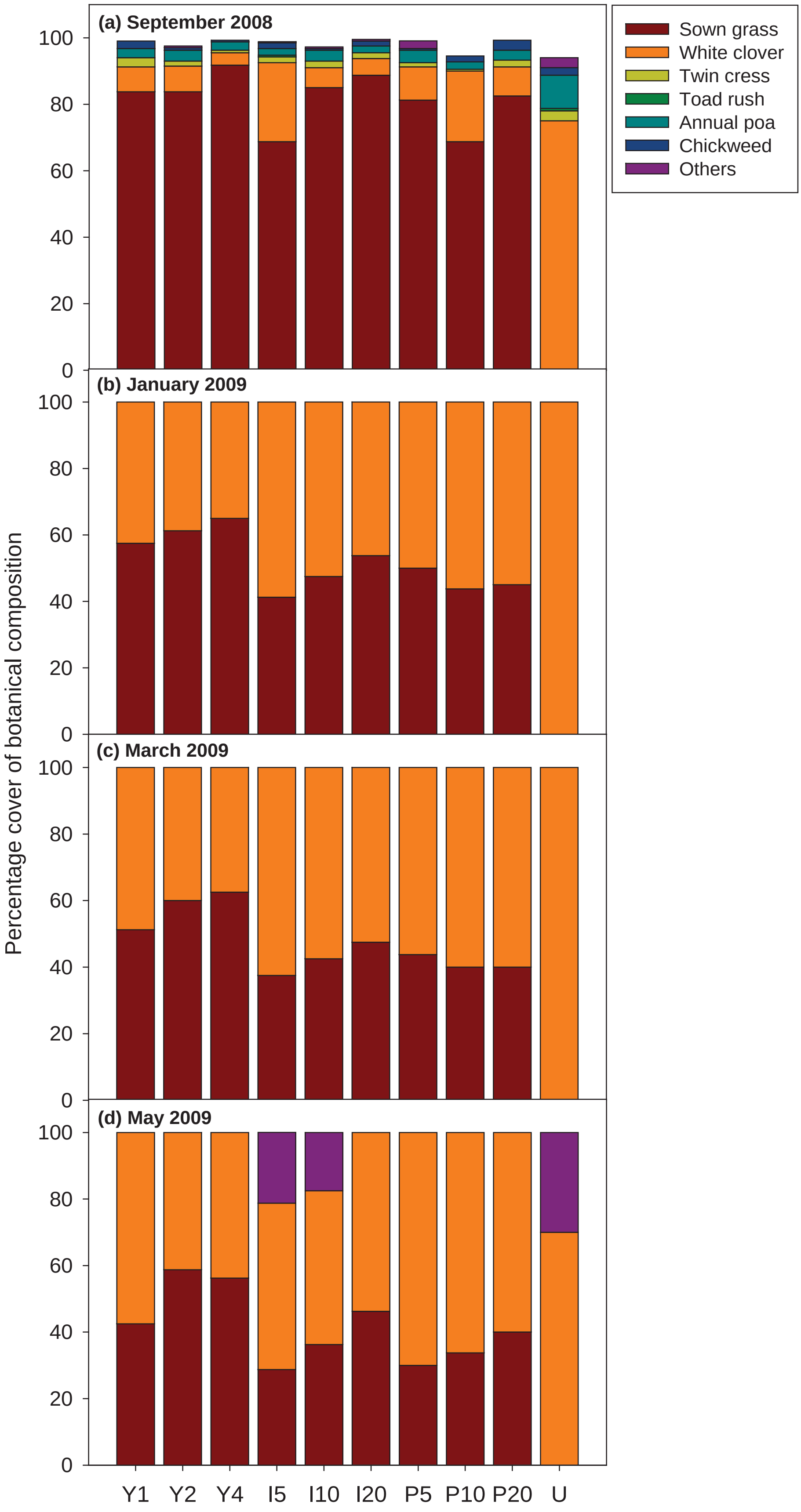


Figure 3.9. Mean percentage plant composition in the Autumn Experiment.

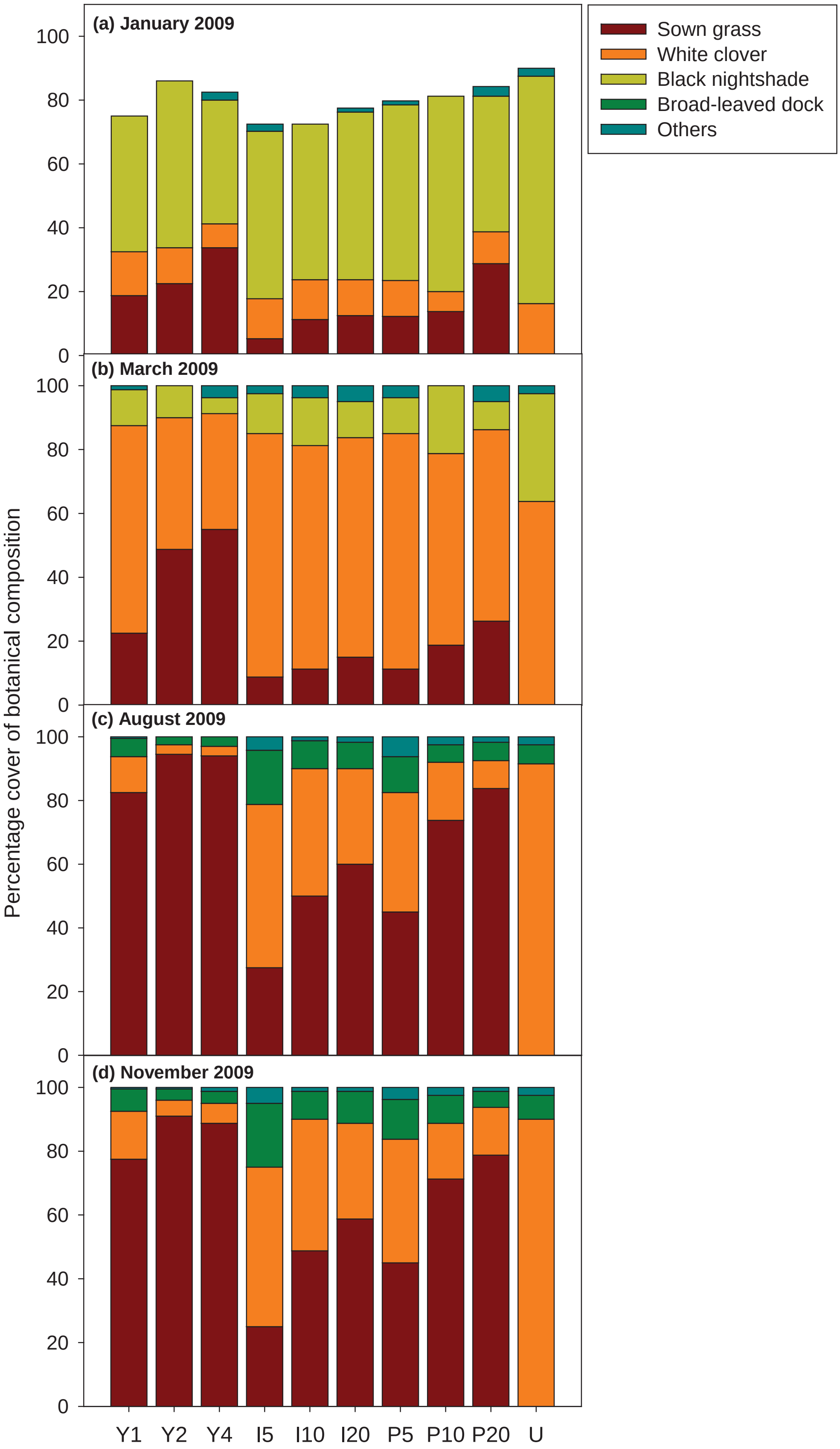


Figure 3.10. Mean percentage plant composition in the Spring Experiment.

Table 3.4. Results of repeated measure analysis of variance testing the effects of sowing species, sowing rate and time after treatment (months) on percentage cover of sown grasses in the Autumn and the Spring Experiments. Bold values indicate statistically significant effects at $P < 0.05$.

Effect	*Autumn Experiment*		*Spring Experiment*	
	F^1	*P*	*F*	*P*
Sowing species (SP)	$59.06_{(2,33)}$	**<0.0001**	$57.30_{(2,31.1)}$	**<0.0001**
Sowing rate (SR)	$1996.50_{(3,33)}$	**<0.0001**	$213.14_{(3,31.1)}$	**<0.0001**
SP × SR	$11.93_{(6,33)}$	**<0.0001**	$6.66_{(6,31.1)}$	**0.0001**
Month (M)	$412.18_{(3,86.9)}$	**<0.0001**	$218.54_{(3,71.4)}$	**<0.0001**
M × SP	$1.72_{(6,92.5)}$	0.1253	$4.85_{(6,79.4)}$	**0.0003**
M × SR	$48.19_{(9,94.5)}$	**<0.0001**	$25.91_{(9,83)}$	**<0.0001**
M × SP × SR	$1.86_{(18,94.8)}$	**0.0290**	$1.58_{(18,85.2)}$	0.0838

[1] Note: F test with degrees of freedom in the brackets

3.3.3 Dry matter production

Dry matter production of broom was significantly different between the two sowing seasons ($F_{1,2}$ = 177.71, P = 0.0056) with the broom plants in the Spring Experiment being bigger, ranging from nearly 0.130 kg ha^{-1} (perennial ryegrass at 20 kg ha^{-1}) to approximately 0.210 kg ha^{-1} (Yorkshire fog at 4 kg ha^{-1}), compared to the Autumn Experiment (0.030 kg ha^{-1} across the treatments) (Fig. 3.11). This difference, however, was not affected by sowing species ($F_{2,4}$ = 0.76, P = 0.5235), sowing rate ($F_{3,6}$ = 1.99, P = 0.2173) or by the interactions between sowing season × sowing species ($F_{2,4}$ = 1.28, P = 0.3719) and sowing season × sowing rate ($F_{3,6}$ = 0.92, P = 0.4858) (Fig. 3.11).

Both sowing rate ($F_{3,6}$ = 6.74, P = 0.0239) and sowing season × sowing rate interaction ($F_{3,6}$ = 4.76, P = 0.0500) did have an effect on total dry matter production of the sown grasses and volunteer grasses and weeds (Fig. 3.12). There was a significant effect of sowing season ($F_{1,2}$ = 55.38, P = 0.0176), sowing rate ($F_{3,6}$ = 22.21, P = 0.0012) and a sowing season × sowing rate interaction ($F_{3,6}$ = 26.55, P = 0.0007) on dry matter production of sown grass species. The mean dry matter production of Yorkshire fog and Italian ryegrass in the Spring Experiment was nearly double that found in the Autumn Experiment while in contrast, the mean dry matter production of perennial ryegrass was nearly four times higher in the Autumn Experiment (Fig. 3.12). As a volunteer species, dry matter production of white clover was significantly different depending on the grass sowing rate ($F_{3,6}$ = 26.80, P = 0.0007) and the sowing season × sowing rate interaction ($F_{3,6}$ = 6.61, P = 0.0249) with the Autumn Experiment showing higher dry matter production. Dry matter production of dead materials (roots and stems) did not differ among sowing season, sowing species or sowing rate.

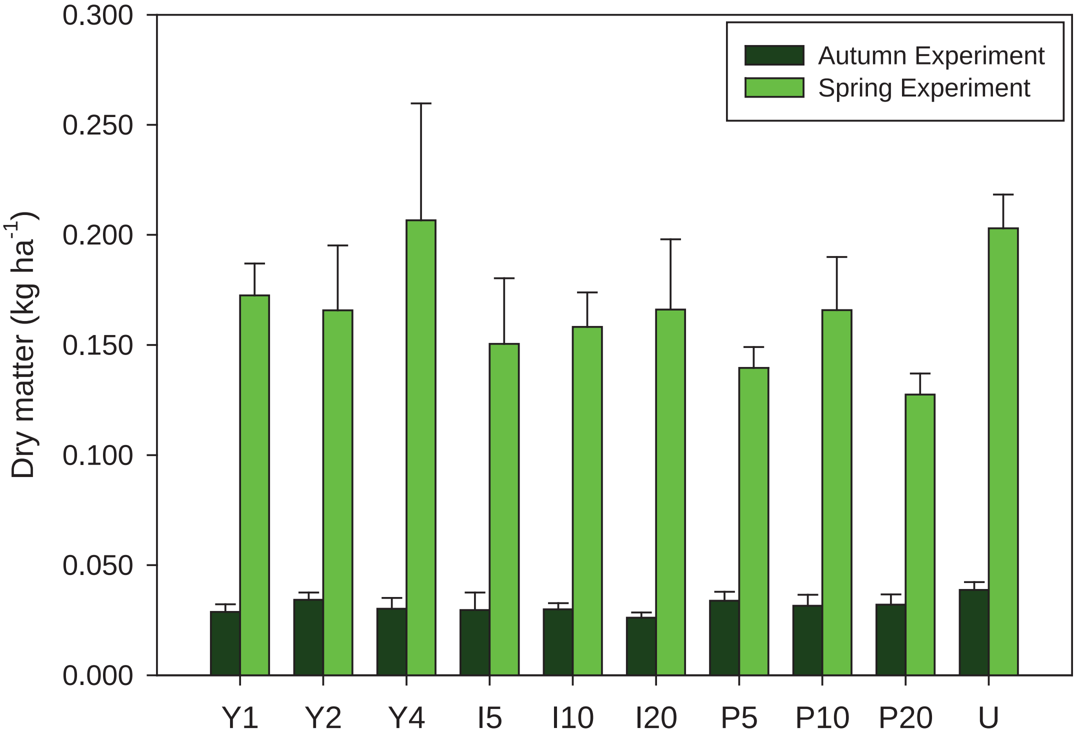


Figure 3.11. Mean dry matter (with one standard error of the mean) (kg ha^{-1}) of broom plants in the Autumn and the Spring Experiments after one year.

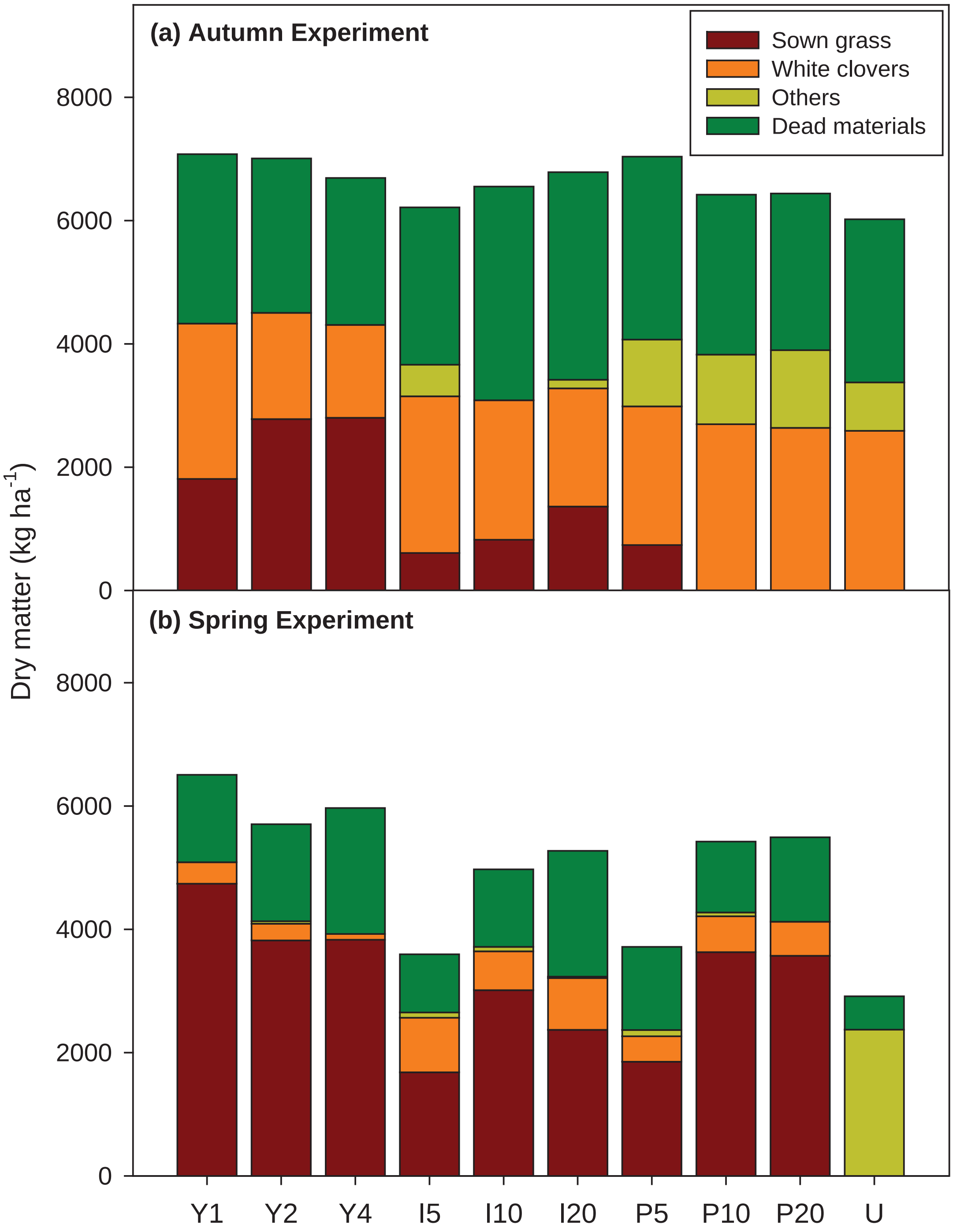


Figure 3.12. Mean dry matter (kg ha^{-1}) of sown grasses and other botanical composition in (a) the Autumn Experiment and (b) the Spring Experiment at the end of experiment (after one year).

3.4 Discussion

It is well known that broom can have large negative effects on growth of newly planted or young *Pinus radiata* (Richardson *et al.* 1997; Richardson *et al.* 1999) and broom can also have a strong influence on tree growth when it is present as an understory species in much older pine stands (Richardson & Whitehead 2002). Vigorous broom seedling regeneration enables dense broom stands to form quickly, increasing hazardous fuels, excluding native plants, and altering community structure of prairies, woodlands, and young forests (Harrington 2007). Broom seedling establishment is the most important life history transition (Parker 2001). Therefore, controlling broom during this stage is extremely important for reducing future invasions to desired crops. Over-sowing of grasses such as Yorkshire fog and lotus (*Lotus pedunculatus* Cav.) between *P. radiata* trees at establishment is one form of weed control in plantation forests practiced in New Zealand (Davenhill 1997).

Harrington (2011) applied an addition series arrangement in greenhouse pot studies to quantify the competitive abilities of three native North American perennial grass species (spike bentgrass (*Agrostis exarata* Trin.), blue wildrye (*Elymus glaucus* Buckley) and western fescue (*Festuca occidentalis* Hook.)) for inhibiting the development of broom seedlings. Regression models predicted 90, 85, and 72 percent reductions in average biomass per plant of broom when grown with approximately 250 plants m^{-2} of bentgrass, wildrye, and fescue, respectively. Bentgrass and wildrye were more competitive than fescue because of their early-season depletion of soil water and rapid development of cover. However, it is difficult to extrapolate these results to field conditions since, in this study, the broom seedlings were transplanted into swards of existing grasses rather than germinating with the grasses. Thus, it might overestimate the effects of grasses on broom seedlings.

In my study, a manipulative approach was applied through creating an artificial broom seed bank and soils cleared from vegetation as expected following a pine harvest on sites with a previous history of broom infestation. Three different types of grasses (Yorkshire fog, Italian ryegrass and perennial ryegrass) sown at three sowing rates in autumn and spring were assessed for their potentially competitive effects on broom seedlings. The results indicated that broom seedling emergence rate was different between the sowing seasons with higher number of broom seedlings emerging in autumn than in spring. The broom seeds used in this study had all been scarified before sowing so perhaps they germinated more readily in the high rainfall and low temperatures that occurred in autumn (May 2008 to August 2008) then in the low rainfall and higher temperatures that occurred in spring (November 2008 to January 2009). The mortality of broom seedlings was also different between the two seasons but not among the treatments. In the Autumn Experiment, Yorkshire fog (three sowing rates combined) gave the best suppression with 47.6% mean broom mortality followed by Italian ryegrass (44.0%) and perennial ryegrass (42.7%) in comparison with the untreated control (32.1%). By contrast, the sown grasses in the Spring Experiment did not perform well with a low rate of grass establishment and a low rate of broom mortality under Yorkshire fog (10.2%), Italian ryegrass (7.3%) or perennial ryegrass (10.4%) in comparison with the untreated control (1.7%).

Importantly, no broom seedlings emerged in either sowing seasons on the plots sown with Yorkshire fog at 2 kg ha^{-1} (Y2A) or Italian ryegrass at 10 kg ha^{-1} (I10A) six months after the grasses had established. This is presumably attributable to the higher density of the grass sward and root systems in these established plots. Either the seedlings failed to germinate or they germinated but died soon after due to competition from the grasses.

Perennial ryegrass (*L. perenne*) is an aggressive competitor during establishment (Moot *et al.* 2000) and can be successfully established in most temperate New Zealand conditions (Mills *et al.* 2007). Seefeldt and Armstrong (2000) indicated that perennial ryegrass sown at different rates (0, 5, 10, 20, 40 and 80 kg ha^{-1}) with 5 kg ha^{-1} of white clover enhanced its competitiveness against nodding thistle (*C. nutans*), California thistle (*C. arvense*), Scotch thistle (*C. vulgare*), ragwort (*Senecio jacobaea*) and hedge mustard (*Sisymbrium officinale*). However, increases in the perennial ryegrass seeding density did not reduce weed emergence but as the perennial ryegrass density increased, weed biomass decreased and time to flowering increased.

Ivens and Mlowe (1980) found that gorse seedlings were strongly suppressed by perennial ryegrass though competition from pasture species is likely to suppress rather than to kill the gorse seedlings. The results emphasise the importance of establishing pasture grasses as quickly as possible after vegetation clearing in order to limit the problem of seedling reinvasion (Ivens & Mlowe 1980; Popay & Adams 1990). Aided by its nitrogen-fixing ability, gorse and presumably broom also, is able to survive in the face of strong competition so effective control is likely to depend on the additional pressure of grazing animals (Ivens & Mlowe 1980).

In my study, Yorkshire fog seems to be more aggressive than the other sown species in both experiments. This result is in contrast with research of Morton *et al.* (1992) who reported that perennial ryegrass is a superior grass to Yorkshire fog on upland soils with high N status, moderate P status and a high pH. Perhaps the difference is due to the lower pH of 5.2 and lack of N fertiliser in my study. Yorkshire fog had the strongest effects on *Erigeron glaucus* Ker Gawl. (Asteraceae), an abundant native perennial, via direct competition, but it also influenced the soil community in ways that feed back to negatively influence *E. glaucus* and other native species after Yorkshire fog removal (Bennett *et al.* 2011).

The establishment rate of sown grasses was relatively low in all the plots. In the Autumn Experiment, a high percentage cover of sown grass species only occurred four months after sowing (September 2008) perhaps once high rainfall and relative low and stable temperature had occurred. Similarly, a high percentage cover of sown grass species only occurred within nine months after sowing (August 2009) in the Spring Experiment. Although the heights of sown grasses were relatively high in comparison with those of broom plants during the first months of the experiments, the relative low percentage cover of grasses was apparently not effective in suppressing or killing broom seedlings. The significantly faster rate of growth of broom compared to that of either of sown grass species and volunteer species could give it an important competitive advantage by allowing it to pre-empt resources at an early stage of the growing season (Lambers & Poorter 1992). Although the loss of biomass through leaf fall in the summer could partially negate this advantage, broom's photosynthetic stems and twigs assist the maintenance of broom height and growth (Fogarty & Facelli 1999).

Over the course of the study, there was a relatively high turnover in the botanical composition of the swards in the two experiments and a lot of incursion of volunteer species. Thus, it is hard to separate out the effects of these volunteer species from the sown species. Among these incursions, white clover became dominant in all treatments with a relatively high percentage cover. This may not always be the case, since Thomas (1984) indicated that white clover in mixes with perennial ryegrass was more suppressed by grasses when drought as a result of its smaller root systems and less able to compete for water.

3.5 Implications for management and future research

This study showed that broom seedlings could be successfully controlled by ground covers but only when the over-sowing of grasses has been applied six months before broom germinated. Thus, over-sowing of grasses in autumn seems to be a suitable option to get better control of broom. However, the use of over-sowing species must be incorporated with the application of selective herbicides that kill broom seedlings that germinate but not the grass sward itself so that the grass will then suppress further broom from establishing. Ground covers alone will not be suitable for broom control if the broom seedlings establish at the same time as the grass. When soil is prepared for planting of pines in New Zealand, existing weeds are often treated using a mixture of metsulfuron-methyl and glyphosate (Davenhill 1997). However, metsulfuron-methyl residues can affect the establishment of crops grown in soil soon after treatment (Rahman *et al.* 1991). As a result, *P. radiata* seedlings are therefore not recommended to be transplanted into treated soil within two months of spraying (Young 2013). Harrington and He (2010) showed that if sowing ground covers in April, application of metsulfuron-methyl can be safely applied until January without affecting the seedlings. However, if sowing in September, residues from metsulfuron-methyl may persist for up to seven months after an autumn/winter application. More research is needed on the type and timing of herbicide applications to improve the rates of establishment of grasses in forest sites before planting *P. radiata* to reduce the risk of the release and establishment of substantial number of broom seedlings from soil seed bank. The application of selective herbicides to remove grasses and broom seedlings after planting *P. radiata* may also be beneficial. The use of herbicides, especially clopyralid, triclopyr and picloram and the appropriate application rates needed to be effective for broom suppression will also needed to be explored in field trials.

CHAPTER 4
PERSISTENCE OF RESIDUAL HERBICIDES FOR PREVENTING THE ESTABLISHMENT OF BROOM (*Cytisus scoparius*) SEEDLINGS

4.1 Introduction

In young forest plantations, competing vegetation such as weeds is often an important constraint for the growth and survival of crop tree seedlings or young trees (White *et al.* 1990; Balandier *et al.* 2006; Wagner *et al.* 2006). Non-crop plant species compete and reduce crop tree growth by using water, nutrients and light (Nambiar & Sands 1993; Löf 2000; Wang *et al.* 2000; Richardson & Whitehead 2002) and therefore the most common reason for practising forest vegetation management is to improve crop tree survival and growth rates by channelling limited resources into the crop rather than associated non-commercial species (Balneaves 1982; Walstad & Kuch 1987). Therefore, weed control is normally undertaken during the period of crop establishment (Richardson *et al.* 1996a).

Broom (*Cytisus scoparius*) is a large, deciduous leguminous shrub that can grow rapidly to form dense stands, quickly excluding native plants and altering community structure of prairies, woodlands and young forests (Bossard & Rejmánek 1994; Wearne & Morgan 2004; Caldwell 2006; Prévosto *et al.* 2006; Wearne & Morgan 2006). Broom is one of the most serious weed competitors of *Pinus radiata* plantations in New Zealand (Richardson & Whitehead 2002). The populations can expand quickly with mature broom plants producing approximately 2000–3500 pods annually with up to 9 seeds exploding out of each pod when ripe (Zielke *et al.* 1992; Peterson & Prasad 1998) and so seed rain can reach up to 21,000 seeds m^{-2} at Lincoln, New Zealand (Paynter *et al.* 2010). Broom seeds have a hard seed coat and form a large persistent seed bank in which seeds can remain viable for up to 81 years (Turner 1933). The combination of high seed production and long dormancy allows broom seed banks to accumulate under dense stands (Oneto *et al.* 2010), for example, up to 16,900 seeds m^{-2} were found in a 9-year-old *P. radiata* stand (Chapter 2) and 36,000 seeds m^{-2} were estimated in a newly planted *P. radiata* stand (Chapter 6). These persistent seed banks make long-term management of the weed difficult (Oneto *et al.* 2010).

Use of ground cover species alone may not be suitable for preventing broom seedlings that establish as the same time as grasses (Chapter 3). The routine application of herbicides during the plantation establishment phase (Richardson 1993), therefore, plays an important part in successful management and control of broom. Effective chemical weed control is preferred over manual weeding and over-sowing of cover crop species, due to the relative costs and benefits of control (Gous 2005). The most prominent use of selective herbicides is to suppress competing vegetation so that desired trees can regenerate and grow more quickly (Gratkowski 1975; Morash & Freedman 1989). A very important determinant of herbicide success is the persistence of the herbicide in the soil and consequently how long following application the herbicide will continue to prevent seedling emergence (Ketchum & Rose 2003).

Herbicide persistence (or residual activity), usually expressed as the half-life (DT_{50}), which is the time taken for its activity to be reduced by 50% through dissipation from soil (Helling 2005), can be assessed by two ways. Half-life can be assessed by bioassays (Rahman & Cox 1975) or by analysing the herbicide residue levels in soil samples using gas chromatographic methods (Roy *et al.* 1989). Bioassays that measure the time required before the bioassay species can successfully grow within treated soil (Günther *et al.* 1989) are simpler than chemical tests and more directly test the persistence of the herbicide on the target weed. The persistence of herbicide residues within soil varies depending on herbicide chemistry, soil properties (soil type and soil organic matter), meteorological factors (temperature and rainfall) and microbial degradation and activity (Helling 2005).

A recent survey of New Zealand forest companies has shown that the major herbicides used by the planted forest industry are terbuthylazine, glyphosate, hexazinone, clopyralid, metsulfuron-methyl, triclopyr and picloram (Rolando *et al.* 2013). However, two of the three most widely used herbicides in New Zealand planted forests, terbuthylazine and hexazinone, are ordinarily prohibited for use in forests certified by FSC (Forest Stewardship Council 2007) but continue to be used temporarily in New Zealand while alternatives are sought (Rolando *et al.* 2013). A derogation is currently granted to permit forest owners temporary use of the prohibited chemicals subject to restricted use controls and research into alternative chemical and non-chemical vegetation control (Rolando *et al.* 2013). However, until a decision is made, both terbuthylazine and hexazinone remain prohibited based on criteria relating to their persistence, and/or toxicity in the environment (Rolando *et al.* 2013).

Among residual herbicides, hexazinone provides better contact activity and residual control of a range of perennial weeds when applied in the spring rather than in the winter soon after planting, persisting up to two years when applied at 4000 g a.i. (active ingredient) ha^{-1} (Cameron & Stokes 1978). In Washington and Oregon (USA), hexazinone applied at 2200 g a.i. ha^{-1} provided both effective and lasting control of grasses and forbs during pre-planting and post-planting applications (Dimock *et al.* 1983). Research conducted in southern New Mexico with the applications of hexazinone at 560 and 1120 g a.i. ha^{-1} showed early season grass and forb control of 65 and 90%, respectively (Fisher *et al.* 1986). Although the rates applied in these studies were safe for conifer growth, higher rates (6000–8000 g a.i. ha^{-1}) were found to increase mortality of *Pinus taeda* L. (Fitzgerald & Fortson 1979).

Hexazinone is degraded by light and microbial activity to various breakdown metabolites and is also readily leached in soil (USDA-FS 1984a). Hexazinone is a semi-selective, residual, systemic herbicide, absorbed both by the roots and through the foliage (Gous 2005). Once absorbed, hexazinone prevents the production of chemical energy by blocking the flow of electrons through the photosynthetic system (Böger & Sandmann 1989). Hexazinone is very active both as a foliar spray or when applied to the soil (Rahman 1981) and is usually applied once or twice per forestry rotation (Michael *et al.* 1999). Its use as a soil-applied residual treatment to control woody weeds has also been reported (Bowers & Porter 1975; Coackley & Moore 1977; Preest 1980). The persistence of hexazinone seems to vary widely with soil type, environmental conditions (Rhodes 1980; Rahman 1981; Harrington *et al.* 1982; USDA-FS 1984a), and timing of application (Coackley & Moore 1977), with the half-life ranging from 10–180 days (Gaskin & Zabkiewicz 1986; Khan & Liang 1989; Michael & Neary 1993). For example, hexazinone was persistent longer on cold and dry sites than under warm and wet conditions and more mobile in a sandy loam soil than in a silt loam soil (Rahman 1981) and these results were in agreement with other studies in North America (Rhodes 1980; Feng 1987; Roy *et al.* 1989) and New Zealand (Close *et al.* 2008; Sarmah *et al.* 2009). Coackley and Moore (1977) assessed the residual activity of hexazinone at various *P. radiata* plantations and under different climatic conditions throughout New Zealand and suggested that the optimum time of application was September (early spring) during the period of active weed growth when there is high plant metabolic activity and less leaching, resulting in longer residual control (Coackley & Moore 1977).

Terbuthylazine is residual herbicide used by itself or in mix with hexazinone, absorbed mainly by roots but also through the foliage (Lavy *et al.* 1989; Gous 2005). Adsorption of terbuthylazine has been found to be strongly influenced by organic carbon (Dousset *et al.* 1994; Wang *et al.* 2010) and pH (Weber *et al.* 1968; Best *et al.* 1975). The majority of New Zealand plantation forest soils are characterised by high organic carbon and low pH, capable of retaining terbuthylazine and reducing the likelihood of leaching loss to groundwater and surface-water bodies (Watt *et al.* 2010). Its tolerance by coniferous trees makes it a popular choice in forestry (Lavy *et al.* 1989). It is one of the most commonly used herbicides in *P. radiata* plantations in New Zealand (Wang *et al.* 2010) for pre- and post-emergent control of annual and perennial grass and broadleaf weeds (James *et al.* 1998; Gous 2005). The half-life of terbuthylazine in the soil has been reported to vary between 5 and 116 DAT depending on soil characteristics and temperature (Sahid & Teoh 1994; James *et al.* 1998). In New Zealand, a hexazinone/terbuthylazine mixture applied as a spot-release for weed control has a half-life of activity of 30–180 days for hexazinone and of 30–60 days for terbuthylazine (Potter & Kriticos 2007).

As metsulfuron-methyl is not tolerated by radiata pine, this herbicide is only used for site preparation. Metsulfuron-methyl is generally considered to have high soil activity and a relatively long residual life in the soil (Beyer *et al.* 1988; Günther *et al.* 1989) with the principal modes of degradation being microbial breakdown and chemical hydrolysis (Beyer *et al.* 1987) and high persistence and mobility depending on environments (Sarmah *et al.* 2000). Chemical hydrolysis is the major degradation pathway for sulfonylurea herbicides (Sarmah *et al.* 1998) and there is a negative relationship between sorption and soil pH (Walker *et al.* 1989; Walker & Welch 1989). Rahman *et al.* (1991) reported that the persistence of metsulfuron-methyl was shorter in soils with lower pH and/or high organic matter and phytotoxic residues differed between time of applications (autumn > spring). Results from other trials in New Zealand soils have shown that metsulfuron-methyl is only moderately mobile with short to medium persistence (James *et al.* 2004). Metsulfuron-methyl has been used to control many broadleaf and woody weeds like broom, gorse and blackberry in New Zealand (Davenhill & Freest 1986; Rahman *et al.* 1991; Davenhill 1997) with a residual effect that lasts for approximately 30 days (Gous 2005).

Another herbicide used for clearing scrub weeds prior to planting pine forests is triclopyr, applied either by itself or in combination with picloram (Davenhill 1997). When used prior to planting pines, rates as high as 6000 g a.i. ha^{-1} are recommended, but it can also be used selectively over new pine plantings for controlling young broom plants at rates of up to 1200 g a.i. ha^{-1} (Young 2013). Triclopyr is a phytotoxic pyridine compound that has been developed to control broadleaf weeds and brush (Jotcham *et al.* 1989). The persistence of triclopyr in soil is variable with the half-life ranging from 10 to 100 days (Cox 2000). Triclopyr applied at 2640 g a.i. ha^{-1} was moderately persistent in some Canadian sandy and clay forestry soils with times to 50% and 90% disappearance at 14 and 20 DAT, respectively, regardless of soil type (Stephenson *et al.* 1990).

The two pyridine herbicides, clopyralid and picloram, are used within New Zealand radiata pine forests. However , picloram is normally used in combination with triclopyr for both site preparation and at lower rates for selective control, while clopyralid is used with triclopyr and picloram for selective control of young broom in establishing pines (Davenhill 1997; Young 2013). Both picloram and triclopyr are selective herbicides, but picloram aerially sprayed at 1100 g a.i. ha^{-1} on gorse can provide soil residues for up to 450 days (MacDiarmid 1975). In comparison to picloram, triclopyr residues were not detected at 120 days after the application of 12,000 g a.i. ha^{-1} (MacDiarmid 1977). Clopyralid can persist and remain active for 60–420 days depending on the rate applied and environmental conditions (Pik *et al.* 1977; Bovey & Richardson 1991; Cox 1998). It is normally used in conjunction with other herbicides such as triclopyr and picloram (Potter & Kriticos 2007). Clopyralid is absorbed by the foliage and residues can persist under field conditions for 60–420 days (Cox 1998) depending on soil type, soil microbial activity, climatic conditions such as temperature (Pik *et al.* 1977; Smith & Aubin 1989) and management practices (Ahmad *et al.* 2003). Once absorbed by leaves and roots of weeds, clopyralid moves rapidly through the plant and affects nucleic acid synthesis and plant growth (Zhao *et al.* 2011).

The persistence of these herbicides, whether used during site preparation or selectively after establishment of radiata pine, may give useful control of new broom seedlings in days following their application. Although there is some information relating to herbicide residual activity, the published figures of herbicide persistence outlined above are often broad ranges and do not refer specifically to ongoing impacts on broom, which may bemore susceptible or tolerant than species used to determine persistence in these studies. Using the herbicides that most widely applied within radiata pine plantations in New Zealand, the objective of this research was to determine their relative persistence and effect over time on broom seedling survival and growth.

4.2 Materials and methods

4.2.1 Study site

This experiment was conducted in a pasture (40°23'S, 175°36'E) at the Moginie Pasture and Crop Research Unit of Massey University, Palmerston North, New Zealand from November 2008 to December 2009. Average monthly temperature and rainfall during the time of the experiment (collected by the Grasslands AgResearch weather station approximately 1 km away from the study site) are shown in Fig. 4.1. The maximum daily temperature ranged from 22.6°C in January to 11.8°C in June.

The soil was a Tokomaru silt loam and samples taken from the trial site had an average pH of 5.2. Olsen-P was measured at 43 μg mL^{-1} and the Na, Mg, K and Ca levels averaged 0.16, 0.74, 0.77 and 3.2 me 100 g^{-1}, respectively. Soil organic matter averaged 5.3% and average CEC was 13 me 100 g^{-1}.

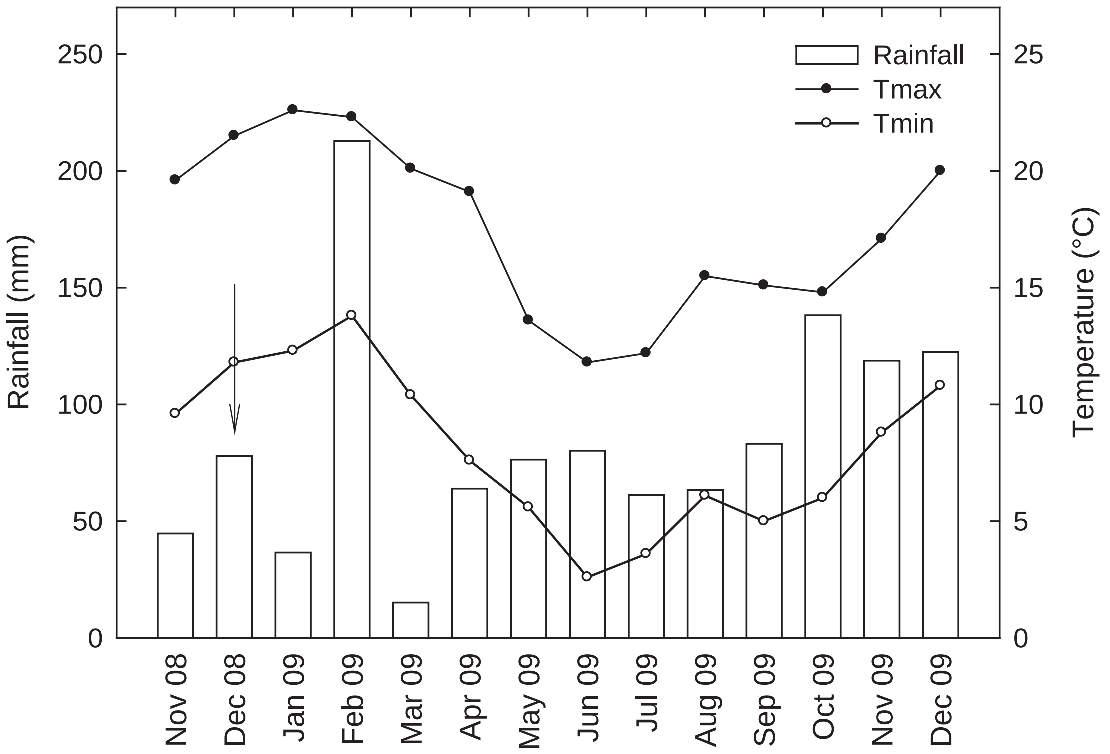


Figure 4.1. Mean total monthly rainfall (mm) and mean monthly maximum (Tmax) and minimum (Tmin) temperature (°C) over the duration of the experiment. The arrow shows the time when herbicide treatments were applied.

4.2.2 Field treatments

The site was cleared on 19 November 2008, two weeks before the start of the experiment, using glyphosate to kill all pasture species present. Thirty-six plots of 1 m^2 (1 × 1 m) were then pegged out with 1-m strip buffers between each plot to eliminate the possibility of contamination from adjacent plots (Fig. 4.2). The experiment was a randomised block design consisting of three blocks (replicates) of 12 treatments comprised of six herbicides, including some treatments which were applied at two rates (standard and double), and an untreated control (Table 4.1). For the treatments applied at two rates, the lower doses were applied at the spot-spraying rate of 1000 L ha^{-1}, simulating "gun-and-hose" spot-spraying as used in forestry, and the higher rates simulated overdosing of 2000 L ha^{-1}. Each herbicide was applied evenly within the allocated plot using a hand-held sprayer on 4 December 2008 at a rate of 3000 L ha^{-1}, spraying back and forth until all the measured amount of solution had been applied.

Some weeds established in the untreated plots and also some of the less persistent herbicide plots. This vegetation was not wanted as the roots could regrow in the bioassay pots described below. Therefore, any vegetation present in the plots was removed using glyphosate (Roundup Transorb at 17 ml L^{-1}) on 22 December 2008 then glufosinate (Buster at 10 ml L^{-1}) on 22 January 2009. Both of these herbicides are deactivated on contact with soil (Young 2013) so would not have affected the trial.

Figure 4.2. Layout of the field experiments at Moginie Pasture and Crop Research Unit (Massey University) showing four blocks of 12 treatments with 1-m strip buffers.

Table 4.1. Herbicide treatments used in the trial.

No.	*Active ingredient (rate, g a.i. ha $^{-1}$)*	*Trade name(rate)*	*Treatment code*
1	metsulfuron-methyl (100)	Escort (0.167 kg ha^{-1})	metsul-L
2	metsulfuron-methyl (200)	Escort (0.333 kg ha^{-1})	metsul-H
3	clopyralid (1500)	Versatill (5 L ha^{-1})	clopyr-L
4	clopyralid (3000)	Versatill (10 L ha^{-1})	clopyr-H
5	hexazinone (3750)	Velpar DF (5 kg ha^{-1})	hexa-L
6	hexazinone (7500)	Velpar DF (10 kg ha^{-1})	hexa-H
7	terbuthylazine (5000)	Gardoprim (10 L ha^{-1})	terbu-L
8	terbuthylazine (10000)	Gardoprim (20 L ha^{-1})	terbu-H
9	terbuthylazine /hexazinone (8500/1500)	Valzine (20 L ha^{-1})	terbu/hexa
10	triclopyr /picloram (3000/1000)	Tordon Brushkiller (10 L ha^{-1})	tric/pic
11	triclopyr (6000)	Grazon (10 L ha^{-1})	triclo
12	untreated control	NA	untreated

4.2.3 Soil sampling and bioassay assessment

To determine whether herbicides in each of the plots were still at high enough concentrations to affect establishment of broom, soil samples were taken at regular intervals from the plots and broom seeds were sown in the soil samples within a glasshouse as a bioassay of activity. The first batch of soil samples was taken one day after the residual herbicides were applied and subsequently at 2-week intervals using a soil corer (2.5 cm in diameter and 5 cm in depth) (Fig. 4.3). Three cores were randomly extracted from each treatment plot with 108 soil samples taken at each sampling time (3 replicates plot^{-1} × 12 treatments × 3 blocks). The soil cores sampled from each plot were mixed in a paper bag and put into pots the same day they were collected before sowing the broom seeds.

Broom seeds were collected from soil on 8 August 2008 from beneath a mature broom plant in a *Eucalyptus* spp. plantation at the Veterinary Large Animal Teaching Unit, Massey University (40°23'S, 175°37'E). The seeds extracted from the soil were laid out on filter paper overnight to dry and then stored in paper bags at 5°C in a storage room before the experiment. Mature hard broom seeds were then selected and scarified using a Forsberg scarifier in which seeds were placed in a drum lined with P100-grid sand paper and rotated 20 seconds to abrade the seed coat. This technique was used as it showed the highest percentage of broom germination under laboratory conditions (Chapter 2) and was therefore suitable for preparing the large number of seeds needed for the bioassay. The scarified seeds were dusted with thiram powder (800 g a.i. kg^{-1} as Thiram 80) to prevent fungal attack and kept in a paper bag before being sown. Plant pots (5 cm × 5cm × 5 cm) were 30% filled with vermiculite before the sampled soil was added to reduce the amount of soil required. Six scarified broom seeds were sown in each pot at a depth of approximately 1 cm. The pots were randomly placed on a bench in a glasshouse at Plant Growth Unit of Massey University (Fig. 4.4) in which the mean monthly temperatures ranging from 16.1°C in October 2009 to 20.3°C in January 2010. Pots were watered three times daily by a subsurface irrigation system to ensure the soil was moist.

Figure 4.3. (A) A sampling plot and (B) a soil core used for sampling.

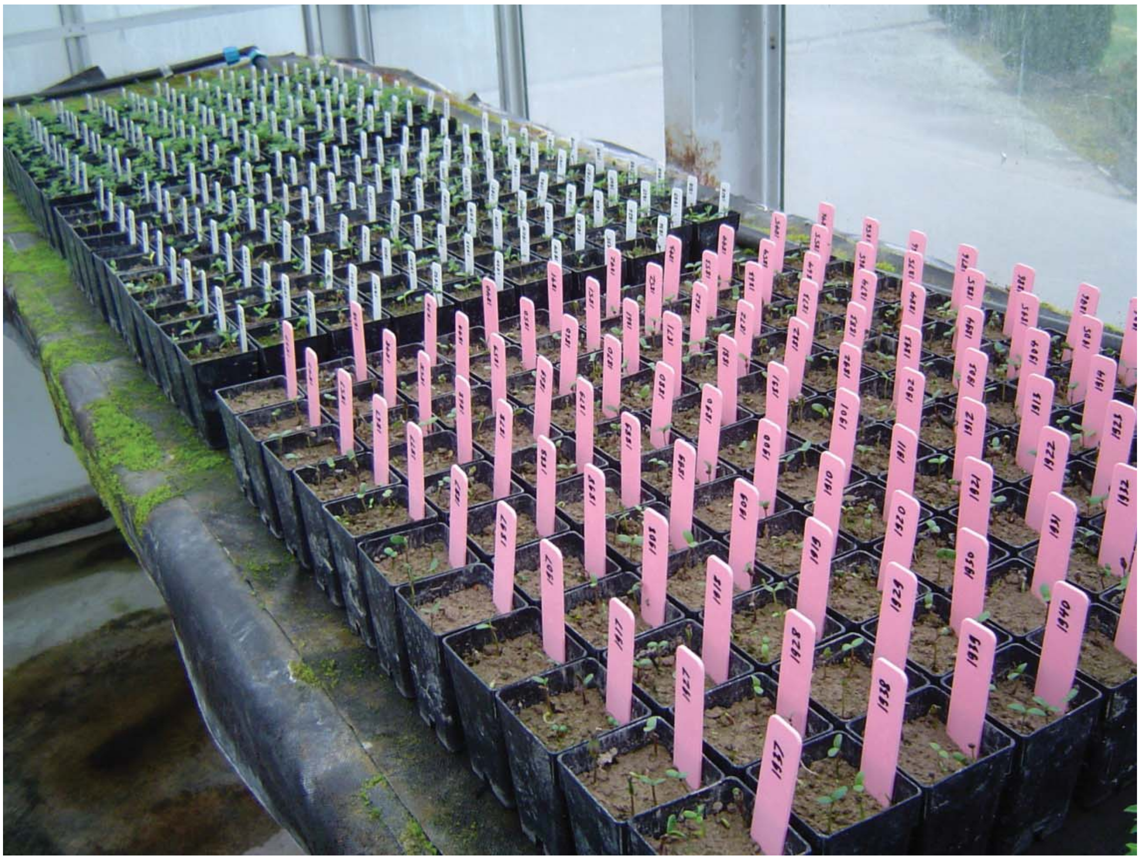


Figure 4.4. Arrangements of batches (sampling times) of treatment pots in a randomised block design in a glasshouse at the Plant Growth Unit (Massey University).

4.2.4 Data collection and measurements

For each batch of broom, the number of live seedlings was recorded fortnightly and the emerged and surviving broom seedlings were assessed for herbicide symptoms such as stunting of stems and discolouration of the leaves/stems using an injury rating system ranging from 0–10 (0, no symptoms (healthy); 1–3, slight; 4–6, moderate, 7–9, severe and 10, death). Each batch of broom seedlings was grown for 60 days, or less if the seedlings had reached a size similar to that achieved after 60 days at the coolest times of the year when growth was slower. At the end of the bioassay, all living broom seedlings from each treatment pot were cut at the base of their stems and the above-ground components oven dried at 80°C to a constant weight. Data on temperature in the glasshouse were collected daily using a data logger.

4.2.5 Data analysis

A preliminary analysis on seedling emergence and survival was performed by fitting an injury symptom curve for each herbicide treatment compared to the untreated control treatment when each batch was harvested to decide when to terminate the sampling for the herbicides. Once there was no difference in injury symptoms between a herbicide treatment and the untreated control treatment, the soil sampling for that treatment was terminated. Although sampling for most herbicide treatments had been terminated by 253 DAT (days after treatment), triclopyr/picloram and terbuthylazine/hexazinone were kept running for 361 days.

All statistical analyses were conducted using SAS 9.2 (SAS Institute Inc. (2008)). For each herbicide treatment sample, survival to 60 days (the number of seedlings that emerged and survived in each pot) and biomass were expressed as a proportion of the untreated control treatment. The data were checked for homogeneity and normality before the analysis using PROC UNIVARIATE. A two-parameter logistic model (Equation 1) was fitted to the repeated measures (batches) of herbicide residues using PROC NLIN and least square estimates of the parameters determined using a Marquardt iterative search algorithm that minimised the residual sum of squares as follows:

$$y = \exp(a + bt)/(1 + \exp(a + bt)) \qquad (1)$$

where y is the probability of seedling survival or relative biomass accumulation, a and b were parameters to be estimated and t was time (days) that each batch was sampled. This logistic model was selected as only two parameters required estimation, allowing predictions to be made with values constrained between 0 and 1. The accuracy of the models was determined by the coefficient of determination (R^2). Plots of residuals against predicted values showed little apparent biases for any of the fitted models.

The estimated time (T_i, days) to 50, 95 and 99% survival (i.e. Ts_{50}, Ts_{95} and Ts_{99}, respectively) and to 50, 75 and 99% biomass (i.e. Tb_{50}, Tb_{75} and Tb_{99}, respectively) were then derived from each nonlinear regression equation. This was undertaken by solving for the number of days after the treatment required to reach 50, 95 and 99% (for survival) and 50, 75 and 99% (for biomass) of the observed survival and/or biomass as a proportion of the untreated control treatment.

Survival rates and relative biomass at 113, 211 and 253 days after treatment (DAT) were analysed with one-way analysis of variance (ANOVA). The logistic parameters *a*, *b* and the obtained T_i, values were also subjected to ANOVA to test the hypothesis of equality between herbicide treatments using the model shown below, that accommodate the underlying randomised block design:

$$Y_{ij} = \mu + \tau_i + B_j + \varepsilon_{ij} \qquad (2)$$

where Y_{ij} is the value observed for treatment *i* and block *j*, μ is overall mean, τ_i is a fixed effect associated with the *i*th treatment (i = 1–11), B_j is a random effect associated with *j*th block (j = 1–3) and ε_{ij} is the random variation. Where there were significant differences among the treatment least square means, a Tukey's honestly significant difference (HSD) test was used to perform multiple comparisons of adjusted treatment means at the significant level $P < 0.05$.

4.3 Results

All herbicide treatments led to visual injury symptoms such as stunting and stem and leaf necrosis but the intensity and effectiveness were highly variable over time (Fig. 4.5). However, the interpretation of the trials is made more complex by variability in the performance of the control seeds through time. The untreated seedlings from the control treatment germinated and then grew poorly initially due to an irrigation system problem in early stages of the trials. However, the difference between the treatments and the untreated control allows the relative performance of each herbicide to be assessed.

Both survival and biomass of broom seedlings under each herbicide treatment expressed as a proportion of the untreated control treatment fluctuated over the course of the study. Although the relationships followed the shapes of sigmoid curves, variability in results meant the fit of the curves to the data varied (Fig. 4.6) with R^2 values ranging from 0.80 to 0.98 (survival) and from 0.61 to 0.95 (biomass). There was variation in seedling survival and injury symptoms among the three blocks of untreated control treatment (Fig. 4.5) and, as a result, there was some uncertainty of exactly when some of the less persistent herbicides stopped affecting the survival and biomass of seedlings.

Metsulfuron-methyl, clopyralid, terbuthylazine, and triclopyr were the least persistent with symptoms no longer different from the untreated seeds after 100 days for both low and high rates (Figs. 4.5 and 4.6). Hexazinone and the terbuthylazine/hexazinone mixture were more persistent, with symptoms visible for up to 150 days. The triclopyr/picloram mixture was the most persistent and prevented broom seedlings from establishing for the longest period, with few germinating in the first 182 days after application (DAT) (Figs. 4.5 and 4.6) and continued to suppress seedling growth for up to 365 days (Figs. 4.5 and 4.6).

The high rate of hexazinone controlled seedlings well for 161 DAT, compared with 147 DAT for the hexazinone/terbuthylazine mixture, 105 DAT for the high rate of clopyralid and 91 DAT for the high rate of terbuthylazine. The high rate of metsulfuron-methyl and the triclopyr treatment were not controlling broom seedlings well after 70 days.

Seedling survival was significantly different among the treatments until 211 DAT (Table 4.2). Treatments can be categorised into three groups with the triclopyr/picloram mixture and the high rate of hexazinone (Group 1) totally suppressing seedling survival until 113 DAT after which seedling mortality reduced from 69 to 47% and 29 to 14% for these treatments at 211 and 253 DAT, respectively. Seedling survival for both rates of metsulfuron-methyl and the low rates of terbuthylazine and triclopyr (Group 3) increased rapidly within weeks of application with only 14 and 22% of seedlings dying under the high rate of metsulfuron-methyl and low rate of terbuthylazine at 113 DAT, respectively. An intermediate group of treatments (Group 2) showed a high variation in seedling survival 113 DAT with 35 and 86% seedling mortality with the high rate of terbuthylazine and low rate of hexazinone, respectively. No significant difference in seedling survival was found between treatments in Groups 2 and 3 from either 211 or 253 DAT.

The relative seedling biomass showed a similar pattern to the seedling survival although the magnitude was significantly different between the most and least effective treatments 113 DAT (Table 4.2). The triclopyr/picloram mixture and the high rate of hexazinone (Group 1) resulted in no seedling biomass until 113 DAT and seedling biomass was reduced to 86% and from 37–27% of the untreated biomass at 211 and 253

DAT, respectively. For the least persistent herbicides (Group 3), the seedling biomass was not much lower 113 DAT, for example only being reduced by 14 and 31% under the low and high rates of metsulfuron-methyl, respectively. As with the mortality data, the intermediate group showed a high variation in relative biomass with 50 and 93% reduction in relative biomass of broom seedlings for the low rate of triclopyr and low rate of hexazinone, respectively. Again, no significant difference in relative seedling biomass was found between treatments in Groups 2 and 3 at 211 and 253 DAT.

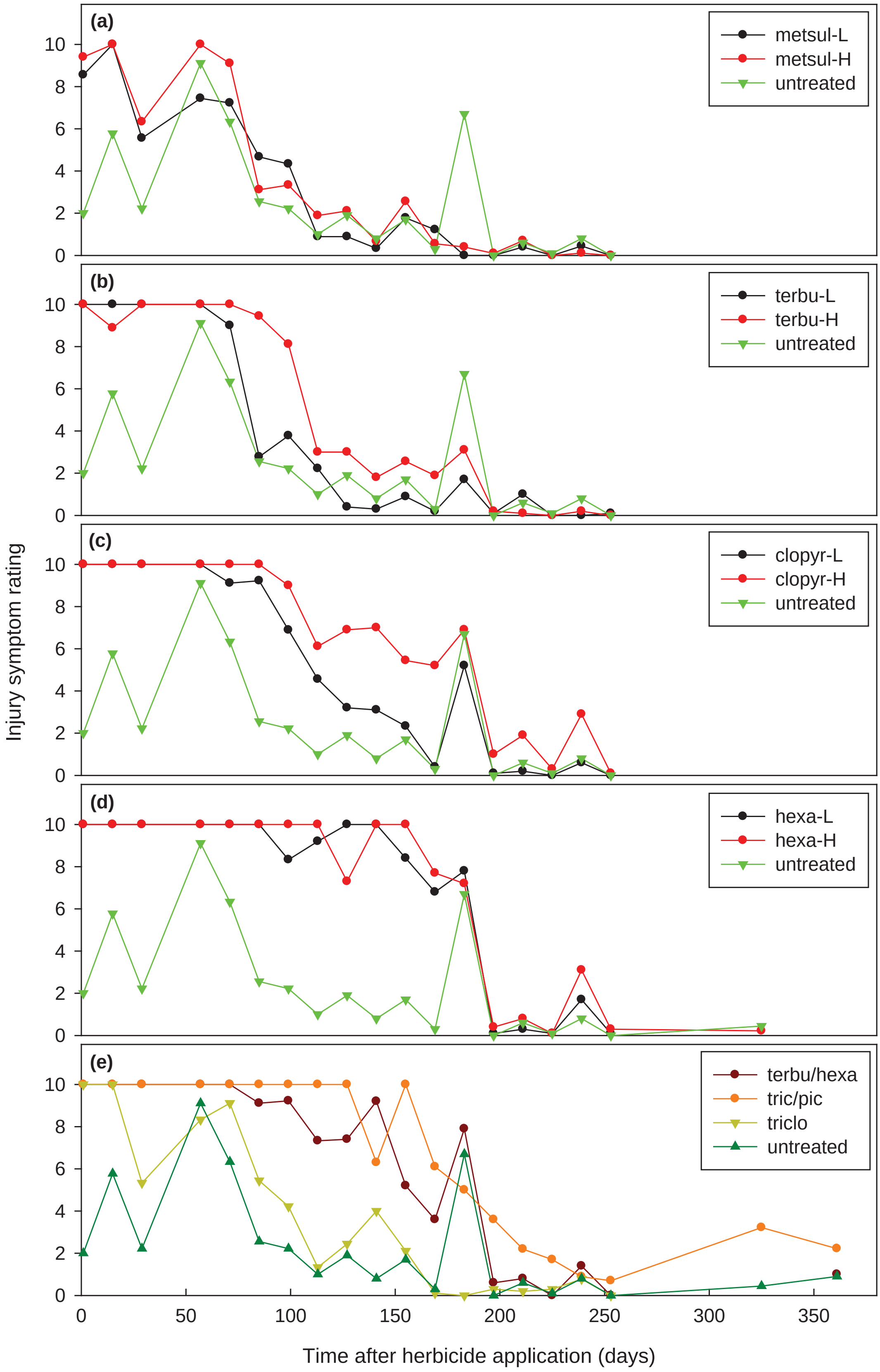


Figure 4.5. Injury symptoms of broom seedlings after the herbicide treatments.

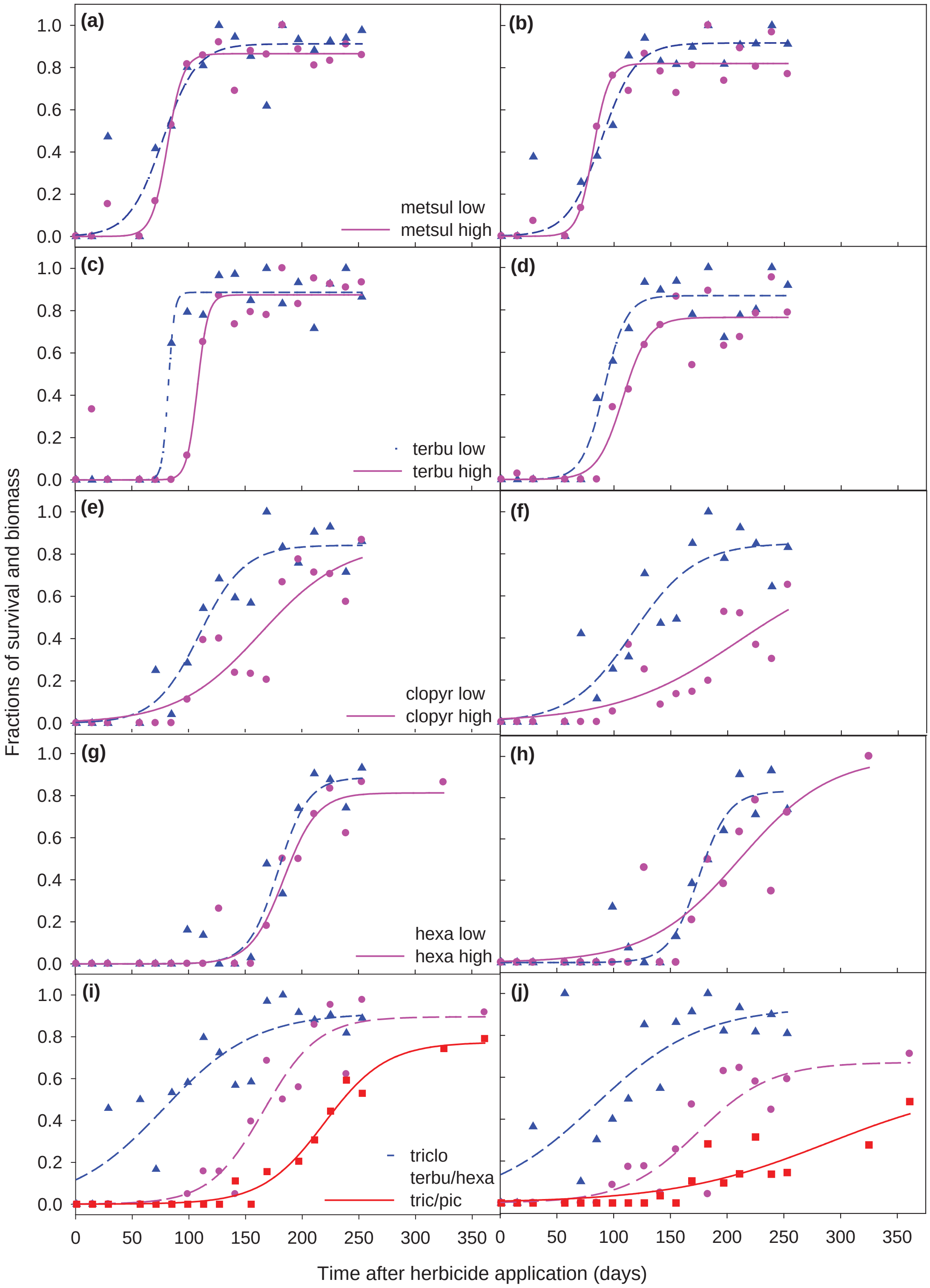


Figure 4.6. Survival (left) and biomass (right) of broom seedlings (expressed as a proportion of untreated control plants) at different times after herbicide treatments had been applied, with curves fitted using logistic models.

Although the logistic model parameters a and b were not different among the treatments ($P > 0.05$) for percentage seedling survival and relative biomass, the estimated time (days) of residual activity differed significantly among treatments (Tables 4.3 and 4.4). With the three estimated times (50, 95 and 99% survival or 50, 75 and 99% relative biomass), only the former is described here as it represents a good indicator of herbicide dissipation. Results presented in the Tables 4.3 and 4.4 can be used in conjunction with the raw data described above to better classify the herbicide treatments into the three groups: (1) long-term (most persistent), (2) medium-term and (3) short-term (least persistent) herbicides with respect to effects on broom seedlings. Using estimates of time to reach 50% seedling survival (Ts_{50}) (Table 4.3), the most persistent treatment was the triclopyr/picloram mixture (246 days) followed by the group with intermediate persistence consisting of the terbuthylazine/hexazinone mixture (176 days), both rates of hexazinone (180–198 days) and the high rate of clopyralid (180 days). The least persistent group consists of both rates of metsulfuron-methyl (73–90 days), both rates of terbuthylazine (83–107 days) and the low rates of triclopyr (91 days) and clopyralid (122 days).

With respect to estimates of time to obtain 50% relative biomass (Tb_{50}) (Table 4.4), the values were slightly greater but similar to the estimates of 50% seedling survival with the most persistent group consisting of triclopyr/picloram (418 days) and the high rate of clopyralid (243 days). The intermediate persistent group included the low rate of clopyralid, high rate of terbuthylazine (both at 131 days), both rates of hexazinone (185–210 days) and the terbuthylazine/hexazinone mixture (228 days). The least persistent group contained both rates of metsulfuron-methyl (87–94 days) and the low rate of terbuthylazine (98 days) and triclopyr (100 days).

Table 4.2. The effects of herbicide residues, 113, 211 and 253 DAT, on actual survival and relative biomass of broom seedlings (% of mean untreated control treatment). Treatments are sorted in an increasing order of damage for 113 DAT. Means within each column followed by the same letter are not significantly different at $\alpha = 0.05$. For the analysis of variance (ANOVA), *F*-values are shown, followed by the *P*-category. Values with one, two and three asterisks are significant at $P < 0.05$, 0.01 and 0.001, respectively and ^{ns} denotes non-significant at $P \geq 0.05$.

Treatment	*Survival*			*Relative biomass*		
	113 DAT	*211 DAT*	*253 DAT*	*113 DAT*	*211 DAT*	*253 DAT*
tric/pic	0.0 d	30.7 b	53.0 a	0.0 c	13.9 b	14.5 b
hexa-H	0.0 d	71.2 ab	86.5 a	0.0 c	63.4 ab	72.8 a
hexa-L	13.7 cd	90.5 a	93.2 a	7.2 bc	91.3 a	74.3 a
terbu/hexa	15.6 bcd	85.7 ab	83.3 a	17.2 bc	64.4 ab	59.1 a
clopyr-L	54.3 abcd	90.5 a	86.0 a	31.1 abc	92.5 a	83.1 a
clopyr-H	39.3 abcd	71.2 ab	86.7 a	36.8 abc	51.7 ab	65.2 a
terbu-H	65.2 abc	95.2 a	93.3 a	42.4 abc	67.2 ab	78.7 a
triclo	79.7 a	88.1 a	88.9 a	49.7 abc	93.3 a	80.9 a
metsul-H	85.7 a	81.0 ab	85.9 a	68.9 ab	89.2 a	76.9 a
terbu-L	77.9 ab	71.7 ab	86.5 a	71.2 ab	77.6 a	91.7 a
metsul-L	81.0 a	88.1 a	97.6 a	85.7 a	90.8 a	91.2 a
Significance of one-way ANOVA ($F_{10,32}$)						
Treatment	7.48^{***}	2.68^{*}	1.50^{ns}	5.43^{***}	4.51^{**}	6.41^{***}

Table 4.3. The estimated time (days) when 50, 95 and 99% survival of broom seedlings was reached. Treatments are sorted in a descending order of herbicide persistence. Means within each column followed by the same letter are not significantly different at $\alpha = 0.05$. For the analysis of variance (ANOVA), F-values are shown, followed by the P-category. Values with two and three asterisks are significant at $P < 0.01$ and 0.001, respectively and ^{ns} denotes non-significant at $P \geq 0.05$.

Treatment	*Logistic model parameters*		*Time to reach % survival (day)*		
	a	*b*	Ts_{50}	Ts_{95}	Ts_{99}
tric/pic	-5.64 a	0.0235 a	246 a	383 a	460 a
hexa-H	-58.67 a	0.3391 a	198 ab	246 abc	272 abc
clopyr-H	-4.30 a	0.0235 a	180 abc	310 ab	382 ab
hexa-L	-70.59 a	0.4339 a	180 abc	207 bc	221 abc
terbu/hexa	-57.18 a	0.3616 a	176 bcd	245 abc	284 abc
clopyr-L	-7.11 a	0.0615 a	122 cde	178 bc	210 bc
terbu-H	-66.91 a	0.6299 a	107 de	167 bc	200 bc
triclo	-2.57 a	0.0256 a	91 e	221 abc	294 abc
metsul-H	-29.72 a	0.3557 a	90 e	170 bc	215 bc
terbu-L	-9.07 a	0.1090 a	83 e	116 c	135 c
metsul-L	-3.12 a	0.0402 a	73 e	159 bc	208 bc
Significance of one-way ANOVA ($F_{10,32}$)					
Treatment	1.02^{ns}	1.09^{ns}	18.02^{***}	5.55^{***}	3.75^{**}

Table 4.4. The estimated time (days) to reach 50, 75 and 99% relative biomass of broom seedlings compared with untreated plants. Treatments are sorted in a descending order of herbicide persistence. Means followed by the same letter are not significantly different at $\alpha = 0.05$. For the analysis of variance (ANOVA), *F*-values are shown, followed by the *P*-category. Values with two and three asterisks are significant at $P <$ 0.01 and 0.001, respectively and ^{ns} denotes non-significant at $P \geq 0.05$.

Treatment	*Logistic model parameters*		*Time to reach % relative biomass (day)*		
	a	*b*	Tb_{50}	Tb_{75}	Tb_{99}
tric/pic	-5.25 a	0.0142 b	418 a	524 a	863 a
clopyr-H	-4.26 a	0.0179 b	243 b	316 ab	549 ab
terbu/hexa	-3.71 a	0.0168 b	228 bc	299 b	527 ab
hexa-H	-5.96 a	0.0281 ab	210 bcd	245 b	375 ab
hexa-L	-72.3 a	0.3872 a	185 bcd	197 b	232 b
terbu-H	-3.65 a	0.0278 ab	131 bcd	176 b	318 b
clopyr-L	-4.00 a	0.0297 ab	131 bcd	169 b	290 b
triclo	-6.21 a	0.0575 ab	100 cd	133 b	237 b
metsul-H	-3.58 a	0.0386 ab	94 d	132 b	249 b
terbu-L	-5.70 a	0.0579 ab	98 cd	126 b	215 b
metsul-L	-4.17 a	0.0453 ab	87 d	118 b	217 b
Significance of one-way ANOVA ($F_{10,32}$)					
Treatment	2.06^{ns}	2.27^{ns}	14.39^{***}	8.92^{***}	4.27^{**}

4.4 Discussion

In this study, the persistence of forestry herbicides was estimated for germinating broom seedlings using three assessments: (1) injury symptoms of survivors; (2) germination and survival of broom seedlings and (3) relative biomass of seedlings compared with the untreated control treatment. All three criteria showed broadly similar patterns suggesting that any of them would be a suitable measure of the residual activity of these herbicides. In the field, broom seedlings are especially susceptible to desiccation because of their limited root systems so even short dry periods would likely result in mortality of seedlings with delayed root development (Ketchum & Rose 2003). As a result, survivorship potential of broom seedlings treated by these herbicides would be expected to be lower under severe conditions (Ketchum & Rose 2003). However, moisture stress in the field may reduce the effectiveness of herbicides by limiting their absorption and movement (Merkle & Davis 1967; Davis *et al.* 1968).

There were some complicating factors affecting the outcomes of criteria used to assess the residual activity of herbicides in this study. The injury symptom scores were an easily, fully described though subjective estimate and accounted for the status of the untreated control treatment. However, scores of the untreated control seedlings 57, 71, and 183 DAT were very sensitive to the low rate of seed germination with high values resulting from few seedlings emerging at the beginning of the experiment. The latter two assessments were fitted using logistic models and the results all showed relatively good fits to the data with high coefficients of determination obtained. However, despite the overall pattern of weakening of suppression, the vigour of broom seedlings varied somewhat erratically through time. Although almost all the curves were fitted quite well with the logistic models, the variation in the survival and biomass of the untreated control treatment is mainly responsible for the different shapes of the logistic curves and these data would have affected the relative survival and biomass of broom under the herbicide treatments. The variation in the seedling survival and biomass of the untreated control treatment was possibly due to: (1) the number of broom seeds sown in each pot (6 seeds) might not be enough to account for poor seed germination and (2) the low germination rates in some untreated control treatments because the irrigation system problem described earlier. These unexpected limitations have somewhat compromised the results on persistence of the herbicides when using relative survival and biomass of seedlings as alternatives to injury symptom scores.

4.4.1 Metsulfuron-methyl

Among the herbicides tested, metsulfuron-methyl was the least persistent even when applied at double the normal rate. Results from my study showed that metsulfuron-methyl killed 80% broom seedlings up to 50 DAT regardless of the rates applied. The timing when 50% germinating seedlings had survived were 73 and 90 DAT for rates of 100 and 200 g a.i. ha^{-1}, respectively. The low rate (100 g a.i ha^{-1}) of metsulfuron-methyl used in my study is similar to the rate recommended to be applied for clearance of scrub weeds in forestry blocks prior to planting *P. radiata* (Young 2013) and that rate is often recommended in conjunction with glyphosate (2550 g a.i ha^{-1}) for better control than either herbicide alone can deliver (Gous 2005; Potter & Kriticos 2007). Metsulfuron-methyl is known to be absorbed through the roots and foliage, and is capable of inhibiting cell division, thereby stopping growth of seedlings (Gous 2005). My results showed that application of metsulfuron-methyl pre-emergence can strongly affect seedling emergence and survival and this is in agreement with the results of Ketchum and Rose (2003) who showed that metsulfuron-methyl gave some control of broom at the operational rates of 30–40 g a.i. ha^{-1}. In another study, Harrington (2009) reported that metsulfuron-methyl applied at 40 g a.i. ha^{-1} remained persistent and killed about 7% of broom seedlings until 90 DAT.

Harrington and He (2010) evaluated the relative susceptibility to metsulfuron-methyl residues of four commonly used ground cover species: Italian ryegrass (*Lolium multiflorum* Lam.), Yorkshire fog (*Holcus lanatus* L.), lotus (*Lotus pedunculatus* Cav.) and pink serradella (*Ornithopus sativus* Brot.) in forestry work. They found that Italian ryegrass was the most tolerant, Yorkshire fog had an intermediate tolerance, and lotus and pink serradella were the most sensitive. To successfully apply the over-sowings of these species in association with metsulfuron-methyl, 60–90 days were required to allow metsulfuron-methyl residues to dissipate prior to an autumn (April) sowing for both Italian ryegrass and lotus without damaging seedlings of these species. However, for spring (September) sowings at least 210 days were required for lotus to be safely sown after metsulfuron-methyl application. This work showed that results could be quite different regarding herbicide persistence if applications occur at cooler times of the year. Metsulfuron-methyl could last quite a long time if it was applied just prior to a cool winter, whereas my trial was done at the beginning of a warm moist summer, so it is likely that the herbicide activity disappeared quickly. Moreover, the relatively low pH

(5.2) in my field experiment would partly be responsible for the high rate of decomposition of this herbicide. These results clearly show the importance of planned seasonal application of herbicides and ground covers in order to obtain a good control of weed seedlings. The implications of using ground covers in conjunction with herbicides will be explored further later in the thesis (Chapter 6).

4.4.2 Triclopyr

Triclopyr was the second least persistent herbicide that only killed 80% broom seedlings 25 DAT with 50% germinating seedlings surviving at 90 DAT when applied at a standard rate of 6000 g a.i. ha^{-1}. The rate used in my trial is the suggested aerial application rate for controlling broom in *P. radiata* plantations in New Zealand (Young 2013) but this herbicide is normally used at lower rates in conjunction with other herbicides such as clopyralid and picloram (Richardson 1993). Residues of triclopyr applied at 3500 g a.i. ha^{-1} to an exotic vine, kudzu (*P. montana*) in loblolly pine (*P. taeda*) regeneration sites were more persistent during a relatively drier period (170 DAT) following the first spot application than during a wet period (29 DAT) (Berisford *et al.* 2006), probably because this herbicide is known to be degraded quickly through microbial activity, which would be favoured by warm, moist conditions (USDA-FS 1984c). The treatments in my trials were applied at the start of summer, but this season was not very dry because of high rainfall in February. Like clopyralid and picloram, triclopyr has no effect on grass species and so can be used to promote a shift in vegetation type to either naturally occurring or sown grasses. These herbicides can also be used in over-sowing operations that predominantly use grass ground covers such as Yorkshire fog (*H. lanatus*) typically sown prior to planting during early autumn. Following establishment, these grasses can reduce germination and establishment of broom seedlings. Moreover, should any broom germinate and establish, clopyralid, triclopyr and picloram can be used to kill the broom during spring without affecting the grass species. These herbicides can also be used for broom control when establishing trees directly onto pasture sites where there is an existing grass cover. Competition from grass immediately around the tree can be removed through spot application of hexazinone/terbuthylazine mixture if permitted, otherwise haloxyfop can be used (Rolando *et al.* 2011a).

4.4.3 Terbuthylazine

Another one of the least persistent herbicides in this group is terbuthylazine with 80% seedlings killed 65 and 95 DAT when applied at the 5000 and 10000 g a.i. ha^{-1}, respectively. The times required for 50% germinating seedlings surviving were 83 and 107 DAT for the two rates, respectively. However, the mixture of terbuthylazine/hexazinone (8500/1500 g a.i. ha^{-1}) gave much better control by killing 80% seedlings 150 DAT. The high rate of terbuthylazine and the terbuthylazine/hexazinone rate used here matched the standard rates of aerial applications used in forestry sites. In my study, suppression of broom seedlings to less than half their normal biomass continued until about 133 DAT. Results from the mixture of hexazinone and terbuthylazine used were intermediate between the two components alone though more similar to hexazinone than terbuthylazine, killing most broom seedlings for about 147 days. Applied in combination at the rate tested here, terbuthylazine and hexazinone is currently the most widely used herbicide for post-plant control of broom. As this mixture has residual activity lasting 150 days and applications are usually made during early to late spring, trees can effectively grow weed-free for almost a year. However, as both terbuthylazine and hexazinone provide control of a broad spectrum of woody and herbaceous weeds these herbicides are not likely to favour establishment of less competitive grass species once residual effects dissipate. Thus, broom seeds that do successfully germinate following dissipation of herbicide residues are likely to take control of the site as this species generally outcompetes other weed species during the establishment phase.

4.4.4 Clopyralid

Clopyralid was a moderately persistent herbicide when applied at the usual rate. Clopyralid applied at the rates of 1500 and 3000 g a.i. ha^{-1} killed 80% broom seedlings up to 85 and 120 DAT, respectively, with 50% broom seedling surviving at 122 and 180 DAT for the low and high rates, respectively. Clopyralid is currently used by some New Zealand forestry companies in release operations for control of broom seedlings that have established among newly planted *P. radiata* at rates as high as 3000 g a.i. ha^{-1}. Tran *et al.* (2010) showed that clopyralid at half of this rate (1500 g a.i. ha^{-1}), when applied with low rates of triclopyr, could kill 12-month-old broom plants without damaging young radiata pine. Given that results show soil residual activity to be markedly less for clopyralid at this lower rate, further research should investigate whether the higher rate of clopyralid has phytotoxic effects on radiata pine, though presumably there would not be a label recommendation for this higher rate if it was unsafe. As clopyralid will not damage grass ground covers and promotes a shift towards naturally occurring grass species, this herbicide, in combination with appropriate rates of triclopyr and picloram, shows the most potential for managing broom within radiata pine plantings. Broom seedlings that germinate along with grass seedlings during establishmentof ground covers can be removed within the first year with these herbicides, and residues will then stop further broom establishment for about another 240 days, by which time grass ground covers should be growing strongly. The broom seedlings that do establish when residues decline will be deformed and stunted, and thus more susceptible to grass competition. In my study, even the low rate of clopyralid (1500 g a.i. ha^{-1}) applied under warm, moist conditions was fairly persistent and killed 50% germinating broom seedlings approximately 120 DAT.

4.4.5 Hexazinone

Hexazinone is also a moderately persistent herbicide that killed 80% broom seedlings 165 DAT regardless of the rates (3750 g a.i. ha^{-1} and 7500 g a.i. ha^{-1}) applied. The effects of hexazinone were still effective at preventing 50% broom seedling survival until 180 and 198 DAT for the two rates, respectively. However, due to the high cost of this herbicide, it is not often used for this purpose and the less expensive glyphosate/metsulfuron-methyl mix is more commonly used to clear existing vegetation prior to planting within New Zealand. The lower rate of hexazinone equated to the highest rate recommended for use in release spraying of radiata pine. However, both rates were able to suppress germination of almost all broom seedlings for about 160 DAT with differences between the treatments becoming more evident after this time had elapsed. Those broom seedlings that did establish after that date were stunted by the remaining herbicide residues, growing to no more than half the biomass of untreated seedlings for approximately another 21 to 49 DAT for low and high rates, respectively. The lower of the two rates used in my study was aimed at mimicking the amount used for releasing *P. radiata* from weeds (Gous 2005) and the higher rate used equates to the maximum rate recommended for pre-plant site clearance (Young 2013). Howerver, hexazinone is normally used at a lower rate in conjunction with terbuthylazine for improved control because these herbicides are well tolerated by *P. radiata* and its persistence enables the herbicide to control weeds for up to 1 year (Rolando *et al.*

2010). Estimates of half-life for hexazinone determined in my study are broadly consistent with previous research. The fitted models for these rates appear to be about 20 days apart. Sarmah *et al.* (2009) determined that the half-life for hexazinone for two New Zealand silt loam soils was 8 and 45 days at 20°C, which is consistent with my result given the temperatures over December and January. They also found the half-life in these two soils increased to 36 and 96 days respectively at 7.5°C, suggesting that if the hexazinone in my trial had not been applied in December but at a cooler time of the year, the persistence would have been longer.

4.4.6 Triclopyr/picloram

Among the herbicides tested, the triclopyr/picloram mixture was the most persistent herbicide and killed 80% of the broom seedlings 170 DAT and reduced 50% of germinating broom seedlings 246 DAT. This is one of the main herbicide mixtures used for release spraying over young *P. radiata* trees in New Zealand. The rates used in my study (3000/1000 g a.i. ha^{-1}) were selected to match the rates for clearing mature broom prior to planting *P. radiata*. This is a much higher rate than that used selectively for release spraying over planted *P. radiata*. Picloram is absorbed by and accumulated in plant roots and foliage in plants such as gorse (Rolston & Robertson 1976; Thai & Field 1979). As mentioned previously, triclopyr persistence in soil is variable (Cox 2000) whereas picloram is moderately to highly persistent in soil. Under highly favourable conditions of moisture, temperature and organic matter, the half-life is approximately 30 days but can last up to four years when applied in arid regions (USDA-FS 1984b). Michael and Neary (1993) reported that picloram applied at a rate of 5000 g a.i ha^{-1} in southern forest ecosystems in the U.S had a soil half-life of 131 days. Although picloram was highly effective in controlling and suppressing broom re-growth at the minimum rate of 1700 g a.i ha^{-1} (Moffat 1966), the low rate of application (100 g a.i. ha^{-1}) was capable of inhibiting growth of white clover (*T. repens*) and red clover (*T. pratense*) 30 DAT (Mason 1966). Picloram is very effective as a residual brush weed herbicide and the residual activity still remained in soil up to 450 DAT when applied at a lower rate (1700 g a.i ha^{-1}) as an aerial spray for the control of gorse (*U. europaeus*) (MacDiarmid 1975). In my study, the triclopyr/picloram mixture was estimated to be capable of reducing the broom seed bank for up to 365 DAT. However, this rate of picloram is not safe for selective use over young pine trees. Rates that are only 10–20% of that used in this trial are recommended for use over young trees to control establishing broom, and even then, there is a risk of tree distortion (Young 2013). Therefore, the triclopyr/picloram treatment tested is only suitable for site preparation, which is normally almost exclusively undertaken using a mixture of the less expensive glyphosate/metsulfuron-methyl (Gous 2005). On sites to be planted in radiata pine that have a pasture cover with some broom present, the triclopyr/picloram mixture could be quite effective as it would conserve the grass cover and leave residues in the soil to discourage anynew broom germination. However, the long residual action of this herbicide may prolong the period following application before trees can be safely planted without suffering damage.

4.5 Implications for management and future research

In summary, this study attempted to assess the residual activity of some forestry herbicides and the results showed that all the herbicides tested have a potential to be used as soil-active treatments to control broom seedlings in *P. radiata* plantations. Apart from suppressing broom seed germination from the seed bank, with all herbicide treatments, there was a period of several weeks or months when the residues were still sufficiently high to stunt the development of new broom seedlings, thereby hindering seedling survival. However, the timing of application is an important factor affecting the residual activity of these herbicides. For example, metsulfuron-methyl seems to dissipate sooner if applied at warmer time of the year (prior to autumn sowing) than at cooler times of the year (prior to a spring sowing) (Harrington & He 2010). Of the six herbicides tested, triclopyr/picloram mixtures had the greatest impact on broom seedling growth and development. In the case of clopyralid, triclopyr, picloram and possibly metsulfuron-methyl, this stunting might make broom seedlings more susceptible to competition from ground cover species such as Yorkshire fog (*H. lanatus*) and lotus (*L. pedunculatus*).

In my study, when used as part of pre-plant and release spraying operations, the relative persistence of residues of the herbicides were triclopyr/picloram > hexazinone > clopyralid > terbuthylazine/hexazinone > terbuthylazine > triclopyr > metsulfuron-methyl. Most herbicides routinely used in forestry have residues that have some effect on the broom soil seed bank. Although triclopyr/picloram mixtures have potential to be used to prepare sites for planting *P. radiata*, as they leave residues that kill and stunt broom seedlings (but possibly also *P. radiata*) for up to a year after application, the cost of application and lack of broad-spectrum control compared with other treatments such as glyphosate/metsulfuron-methyl make it less likely to be used. Other herbicides commonly used in forestry also affect seedlings for many days, especially hexazinone and clopyralid.

The use of these herbicides may be improved if applied at suitable time of the year along with over-sowings of ground cover species. In the field, broom seedling emergence begins once dormancy wears off and this process is often staggered over a long period. Thus, later geminating seedlings may survive better than the early germinants if the residual effects of herbicides are no longer effective. Having ground covers present would be useful at this stage to compete with these seedlings. Consequently, further research is needed on alternative management schemes for broom control to explore the rates and timing of herbicide application in forestry with associated over-sowings of ground covers such as Yorkshire fog (*H. lanatus*). More importantly, research is needed to determine how soon after application *P. radiata* seedlings could safely be planted and whether effective ground covers can be maintained, particularly since these species are also susceptible to some herbicides, especially clopyralid, triclopyr, and picloram. Furthermore, the herbicide rates needed to be effective for broom suppression need to be determined. It is, therefore, of interest to study the susceptibility of these ground covers and of *P. radiata* to these herbicides. Accordingly, a study to investigate these management options for controlling broom seedlings was conducted in a *P. radiata* stand in North Island, New Zealand and the first year of results are reported in Chapter 6.

CHAPTER 5

ASSESSMENT OF HERBICIDES FOR SELECTIVELY CONTROLLING BROOM (*Cytisus scoparius*) GROWING WITH RADIATA PINE (*Pinus radiata*)

5.1 Introduction

Managing weeds at pre-harvest, site preparation (pre-plant) and forest establishment (post-plant) stages of the forest development cycle is an important part in maintaining the future health of plantation forests and is the single most important silvicultural practice used to maximise timber yield (Wagner *et al.* 2006). In New Zealand, the most cost effective vegetation management strategies involve the use of herbicides, both in pre-plant site preparation treatments and for release during the first and sometimes the second year after planting (Rolando *et al.* 2011b). During the forest establishment stage, residual herbicides play an important part in preventing the survival of weeds germinating from the seed bank, while selective knockdown herbicides can release the desired trees from competition with weeds that do manage to establish (Sullivan *et al.* 1998).

In Chapter 4, results on persistence of herbicides applied during pre-plant phase for controlling germinating broom seedings have been reported. A variety of herbicides have been applied to control established broom plants (Peterson & Prasad 1998) at the competition release (post-plant) phase (Potter & Kriticos 2007). The most prominent use of selective herbicides is to suppress competing vegetation so that the desired trees can regenerate and grow more quickly (Gratkowski 1975; Morash & Freedman 1989). Hexazinone is a soil and foliar applied triazine herbicide used to control many annual and perennial broadleaf and grass weeds as well as brush species (Donald 1986). The herbicide is readily absorbed by roots and translocated upwards in the apoplast, but is less readily translocated out of leaves when applied to the foliage (Donald 1986). Symptoms of plants injured by hexazinone include foliar chlorosis followed by necrosis (Donald 1986). Terbuthylazine and hexazinone are currently used in New Zealand forestry to control a range of competitive weed species during the first year after planting *P. radiata* (Gous 2005). These herbicides are widely applied in forestry sector due to their tolerance by *P. radiata* (i.e. no phytotoxic damage) and their soil persistence that provides activity, with either aerial or spot treatment, to reduce weed growth for up to one year (Rolando *et al.* 2011a). However, hexazinone has been known to cause phytotoxic effects in *P. radiata* seedlings when applied at high rates (Preest 1986) and can affect *P. taeda* (loblolly pine) seedlings through root and foliar uptake (Fitzgerald & Fortson 1979; Michael 1985). In contrast, hexazinone used as a spring release application soon after planting has shown excellent safety for conifers in the Pacific Northwest (USA) (Ketchum & Rose 2003). Thus, the toxicity effects on pines can be variable.

Other herbicides such as triclopyr and clopyralid have also been tested for their toxicity to *P. radiata* and selected forest weeds. Triclopyr can control annual broadleaf weeds as well as tree and brush species (Donald 1986). Triclopyr is absorbed by roots and foliage and translocated to the site of action in the target plant where it acts as a synthetic auxin, inhibiting growth of plant tissues (Donald 1986). Triclopyr causes epinasty, including leaf cupping and curling, followed by necrosis in affected tissues (Donald 1986). Picloram can be used for the control of many annual and perennial broadleaf weeds and woody plants, while most grasses are tolerant at label rates (Donald 1986). Symptoms of herbicide injury from picloram include epinasty or curling and twisting of leaves, stems, or roots followed by necrosis (Donald 1986). These symptoms are similar to other plant growth regulators, including triclopyr, aminopyralid, and clopyralid (Donald 1986).

Triclopyr applied at 1800 g a.i. ha^{-1} had no effect on *P. radiata* seedling growth during tree dormancy (Saville 1989). Triclopyr is recommended to be applied at rates from 600–1200 g a.i. ha^{-1} to control broom during the first year after planting (Young 2013). Clopyralid (1500 g a.i. ha^{-1}), used in combination with triclopyr (150 g a.i. ha^{-1}) and picloram (50 g a.i. ha^{-1}), is used by the forest industry to control broom in the second year after planting but the impact of this herbicide combination on younger pine trees has not been tested (Rolando *et al.* 2011a). However, many chemical mixtures like clopyralid/picloram which are effective against broom can cause symptoms in *P. radiata* such as twisting of the trunk if they are not applied carefully (Potter & Kriticos 2007).

The application rate of a herbicide needed for effective post weed control depends on the target weeds for control, age or growth stage of the weeds, and the environmental conditions at the time of herbicide application. Herbicide rates recommended on product labels are set to ensure control of a range of weeds that vary in susceptibility under conditions that may be less than optimal for herbicidal activity. Reduced rates may effectively control susceptible weeds if applied to young weeds when conditions are favourable for growth (Barrentine 1989; Risley & Oliver 1991; King & Oliver 1992). Determining susceptibility of weeds at various growth stages to a range of herbicide rates allows for selection of the most economical, effective herbicide program for a given weed spectrum (Klingman *et al.* 1992).

Broom is normally found in patches of varied ages that were initiated during the *P. radiata* plantation establishment phase. In this situation, the success of broom control depends on the timing of herbicide application and the types of herbicides used. In turn, the effects of herbicides on growth and development of *P. radiata* plants also vary but are clearly important to understand for successful management of pine plantations. The use of herbicides that selectively kill broom plants that have already established with young pine trees are of importance. However, there is little published information on how effective these herbicides are on broom and their safety to young pines. Accordingly, the aims of this study were to investigate (1) the efficacy of six selective forestry herbicides applied at three different rates for controlling broom of various ages (3, 6, 9 and 12 months) in order to test the hypothesis that for a given herbicide rate, efficacy decreases as broom plant age increases; and (2) the tolerance of 12-month *P. radiata* to these herbicides is relatively susceptible to herbicide rates applied.

5.2 Materials and methods

5.2.1 General cultivation methods for broom and Pinus radiata

Broom seeds were collected from soil on 5 November 2007 from beneath a mature broom plant in a *Eucalyptus* spp. plantation at the Veterinary Large Animal Teaching Unit, Massey University (40°23' S, 175°37' E). The seeds extracted from the soil were laid out on filter paper overnight to dry and then stored in paper bags at 5°C before germination. Four cohorts of broom seedlings were subsequently germinated at 3-month intervals (22 December 2007, 23 March 2008, 26 June 2008, and 23 September 2008) to represent different stages of broom development under field conditions. Hard and viable broom seeds were scarified prior to each sowing by nicking the seed coat with a sharp scalpel. After the treatment, 60 seeds were sown in a seed tray containing potting mix at a depth of 1 cm with 240 seeds per cohort (60 seeds × 4 trays). The trays were kept in a heated glasshouse at Seed Technology Services, Massey University. They were checked daily for germination and watered three times per day.

After all broom seedlings had emerged, attained their first true leaves and had reached about 10 cm high, 100 healthy seedlings from each cohort were transplanted individually into 1.2 L planter bags (9 cm diameter × 20 cm depth), containing a long-term fertiliser medium mix (100 L Daltons base mix) containingdolomite (150 g), 3–4 month Osmocote® (100 g), 8–9 month Osmocote® (200 g) and 12–14 month Osmocote® (200 g).

The four cohorts of broom seedlings were then kept inside an unheated shadehouse at Plant Growth Unit, Massey University, watered twice per day and tended until the first cohort of broom had reached 12 months. At the same time, a cohort of 150 9-month *P. radiata* seedlings was bought from a nursery and planted in pots containing the same potting mix as the broom seedlings on 18 September 2008 (Fig. 5.1). Due to limited space in the shadehouse, only *P. radiata* seedlings and the 3-month broom cohort were located in the shadehouse from September 2008, and the other three cohorts of broom seedlings were kept in an area beside the shadehouse, but were still watered each day.

Figure 5.1. A picture showing the preparation of broom and pine plants before the treatment application.

5.2.2 Experimental design

The experiment consisted of 19 independent treatments (6 herbicides × 3 rates, and an untreated control), applied to each cohort of broom and each *P. radiata* seedling using a randomised block design with five replicates (blocks) per treatment (Table 5.1). The three rates represented the current recommended rate, half this rate, and double the rate.

The initial height of each broom and *P. radiata* plant was measured and recorded one day before the application of treatments. Height (cm) was measured from the potting mix surface to the apex of the plant. The health and general condition of each plant was also assessed the same day using a scoring system ranging from 0 to 10 (where 0 = very healthy and 10 = very unhealthy) and this was used to allocate plants to blocks (Table 5.2). The average height of the different broom cohorts differed considerably although there was some variation in the heights of largest broom cohort in comparison with those of other broom cohorts and with *P. radiata* plants.

Table 5.1. Herbicide treatments used in the trial.

No.	*Active ingredient (rate, g a.i. ha^{-1})*	*Trade name (rate)*	*Treatment code*
1	clopyralid/picloram (225/150)	Radiate (1 L ha^{-1})	clo/pic-L
2	clopyralid/picloram (450/300)	Radiate (2 L ha^{-1})	clo/pic-M
3	clopyralid/picloram (900/600)	Radiate (4 L ha^{-1})	clo/pic-H
4	clopyralid/triclopyr (750/150)	Versatill/Grazon (2.5/0.25 L ha^{-1})	clo/tric-L
5	clopyralid/triclopyr (1500/300)	Versatill/Grazon (5/0.5 L ha^{-1})	clo/tric-M
6	clopyralid/triclopyr (3000/600)	Versatill/Grazon (10/1 L ha^{-1})	clo/tric-H
7	clopyralid/picloram/aminopyralid/triclopyr (750/25/2/75)	Versatill/Tordon Brushkiller XT (2.5/0.25 L ha^{-1})	cpat-L
8	clopyralid/picloram/aminopyralid/triclopyr (1500/50/4/150)	Versatill/Tordon Brushkiller XT (5/0.5 L ha^{-1})	cpat -M
9	clopyralid/picloram/aminopyralid/triclopyr (3000/100/8/300)	Versatill/Tordon Brushkiller XT (10/1 L ha^{-1})	cpat -H
10	fluroxypyr (250)	Starane (1.25 L ha^{-1})	fluro-L
11	fluroxypyr (500)	Starane (2.5 L ha^{-1})	fluro-M
12	fluroxypyr (1000)	Starane (5 L ha^{-1})	fluro-H
13	terbuthylazine (5000)	Gardoprim (10 L ha^{-1})	terbu-L
14	terbuthylazine (10000)	Gardoprim (20 L ha^{-1})	terbu-M
15	terbuthylazine (20000)	Gardoprim (40 L ha^{-1})	terbu-H
16	hexazinone (3000)	Velpar DF (4 kg ha^{-1})	hexa-L
17	hexazinone (6000)	Velpar DF (8 kg ha^{-1})	hexa-M
18	hexazinone (12000)	Velpar DF (16 kg ha^{-1})	hexa-H
19	untreated control	NA	untreated

Table 5.2. Mean (with standard error of the mean in brackets) initial heights and general condition (score, with 0 = very healthy and 10 = very unhealthy) of broom and *Pinus radiata* before the treatment.

Species	*Age (months)*	*Height (cm)*			*Condition*
		Mean (SE)	*Minimum*	*Maximum*	
Broom	3	14.8(0.4)	6.5	28.0	2.0
	6	36.7(0.7)	21.0	52.0	1.3
	9	61.7(0.8)	45.0	87.0	1.2
	12	111.7(2.4)	59.0	174.0	2.0
P. radiata	12	42.7(0.3)	35.0	53.0	0.9

Figure 5.2. A picture showing the preparation of broom and pine plant for a herbicide spraying treatment on 18 December 2008.

The individual broom and *P. radiata* plants in pots were treated as experimental units, resulting in 380 replicated pots for broom (5 replicated pots × 19 treatments × 4 cohorts) and 95 replicated pots for *P. radiata* (5 replicated pots × 19 treatments). The herbicide solutions were prepared and applied on 18 December 2008 using a precision gas-powered plot sprayer at a rate equivalent to 300 L ha^{-1}. All herbicide treatments apart from the hexazinone, were applied with an organosilicone surfactant (Boost Penetrant at 0.5 L ha^{-1}). After treatment, all broom and *P. radiata* plants were returned to their original locations either within or beside the shadehouse and were irrigated regularly until the end of the trial (179 days after treatment (DAT)).

5.2.3 Assessment of herbicide effects

The phytotoxic effects of herbicide treatments on broom and *P. radiata* plants were determined by a visual rating system based on the extent of plant necrosis and health, ranging from 0 to 10 (0, no symptom (healthy); 1–3, slight; 4–6, moderate, 7–9, severe and 10, dead) at 2-week regular intervals until 179 DAT. Shoot height and stem diameter were also measured 113 and 179 DAT in June 2009. At the end of the experiment, all broom and *P. radiata* plants were cut at the base of their stems in June 2009 and their fresh weights measured. All harvested plants were oven dried at 80°C to a constant weight then dry weights were recorded.

5.2.4 Data analysis

All statistical analyses were conducted using SAS 9.2 software (SAS Institute Inc. 2008). Treatment effects were considered significant at $P < 0.05$ for all analyses.

Broom

As the first interest was to see how effective the herbicides were on broom cohorts, a separate analysis was performed for each broom cohort. Since the injury data were on an ordinal scale and did not meet the assumption of normal standard parametric methods, a relative marginal effects non-parametric analysis (Brunner *et al.* 2002; Shah & Madden 2004) was used to analyse the injury data collected at the end of the experiment (179 DAT). This method allows for analysis of ordinal data with small sample sizes as was the case in my experiments (5 replicates per treatment). The data were analysed as a one-way analysis of variance (ANOVA) with median ratings calculated using PROC TABULATE and mean ranks found using PROC MIXED. Tukey's honestly significant difference (HSD) tests were used to perform multiple comparisons between all pairs of treatments when ANOVA results indicated significant treatment effects.

In order to test the hypothesis that for a given herbicide rate, herbicide efficacy decreases as plant age (cohort) increases, a two-way ANOVA was performed for each herbicide for four rates (none, half, recommended and double) and four cohorts of broom using the same procedure as above. Relative treatment effects ($\hat{p}_{ij}$) were calculated using the LD_CI macro which allows for generating standard errors, variances and confidence intervals for the $\hat{p}_{ij}$ values (Brunner *et al.* 2002). It can be shown that the estimated relative treatment effect can be determined directly from the observation mean ranks of the injury data, and differences in the $\hat{p}_{ij}$ values are used to compare treatments (Shah & Madden 2004).

Data on dry weights (biomass) were also analysed separately for each cohort. As a number of missing data were present in the 3-month broom cohort as many plants had died and blown away before the final harvest (and thus score as 10 in the visual rating system above), only selected treatments were used in the analysis (i.e. low- and medium-rate clopyralid/picloram, low- and medium-rate clopyralid/triclopyr, low- and medium-rate fluroxypyr, low-rate hexazinone and untreated control). The biomass data were analysed using PROC MIXED using the restricted maximum likelihood estimation method that can handle data sets with missing data. To improve the statistical precision of experiments, analysis of covariance (ANCOVA) was first performed using untransformed biomass data with initial heights used as a covariate to adjust for variation among experimental units (individual plants) within each block (Harrison & Regnier 1990; Littell *et al.* 2006). The data were analysed by testing a slopes-equal-to-zero hypothesis. If the slopes-equal-to-zero hypothesis was not rejected (i.e. slopes were all equal to zero), a common slope model was fitted to the data and the hypothesis that the slope was equal to zero was tested. If this model failed to reject, the covariate was not needed in the model, and the treatment means were compared using ANOVA. Assumption of normality of residuals was checked by PROC UNIVARIATE and since the preliminary results were not normally distributed the biomass data were log(x+0.5) transformed before being analysed to stabilise the variance (Yamamura 1999). The transformed data were then analysed using the same procedure as above. Tukey's honestly significant difference (HSD) tests were then used to perform multiple comparisons between all pairs of treatments when ANOVA results indicated significant treatment effects.

Pinus radiata

With respect to analysis of *P. radiata*, the main interest was to see how safe the different rates of herbicides were as measured by the survival and growth of *P. radiata*. The effects of herbicides were evaluated over the course of experiments by considering the injury data collected at three dates (15, 98 and 179 DAT). As the data were correlated over the course of the experiment, these data were also analysed using a relative marginal effects non-parametric analysis by the same procedure described above for broom cohorts. The data on dry weights (biomass) of *P. radiata* was analysed in the same manner as the broom data.

5.3 Results

5.3.1 Effects of herbicides on broom plants

The types of herbicides and the rates applied both had significant effects on the phytotoxicity rating values compared with untreated control across all broom cohorts (3-month broom cohort, $F_{8.23,33.7} = 14.85$, $P < 0.0001$; 6-month broom cohort, $F_{8.6,35.2} = 7.37$, $P < 0.0001$; 9-month broom cohort, $F_{5.15,20.9} = 11.61$, $P < 0.0001$; 12-month broom cohort, $F_{11.1,45.6} = 14.28$, $P < 0.0001$, Table 5.3), although the magnitude of the effects differed among the herbicides applied. The median "health" ratings ranged from 0 to 3 for the untreated control treatment and from 1 to 10 for the herbicides which resulted in mean ranks ($\overline{R}_{ij}$) ranging from 3.2 to 83.6 for the untreated control treatment and the high rate of clopyralid/triclopyr, respectively across the four broom ages (Table 5.3).

Among the herbicides tested, the low and medium rates of fluroxypyr and the low rate of hexazinone were the least effective and caused only slight or moderate damage to all broom cohorts. The effect of the low rate of clopyralid/picloram was mild on all broom cohorts whereas the medium rate totally killed the 6- and 9-month cohorts and only the 12-month broom cohort tolerated the high rate. The low rate of clopyralid/triclopyr only caused slight and moderate effects on the 3- and 12-month broom cohorts whereas the medium rate was tolerated by the 12-month broom cohort.

The clopyralid/picloram/aminopyralid/triclopyr mixture applied at three rates did not totally kill the 12-month broom cohort but resulted in severe damage to the 6- and 9-month broom cohorts when applied at the low rate. The high rate of fluroxypyr did not totally kill the 12-month broom cohort and nor did the medium and high rates of terbuthylazine. Slight and moderate damage were found with the low rate of terbuthylazine and the medium rate of hexazinone when applied to 9- and 12-month broom cohorts. The results on mean ranks further confirmed this trend (Table 5.3).

The effects of broom cohorts on the efficacy of clopyralid/triclopyr were significant whereas no significant effects were found with other herbicides and mixes whereas the effects of rates were highly significant (Fig. 5.3; Table 5.4). However, the cohort × rate interactions were not significant (Fig. 5.3; Table 5.4).

Changes in broom biomass following the herbicide treatments further confirmed the results from the health scores. The analysis of covariance using initial heights as an independent variable did not improve the result for 3-, 6- and 9-month broom cohorts and therefore the analysis of variance was used as a simple alternative for assessment of the effects of herbicide treatments. The results showed that both the type of herbicides and the rates used had significant effects on the biomass values across these broom cohorts. For the 3-month broom cohort, the herbicide treatments significantly reduced broom biomass compared with that of the untreated control treatment ($P < 0.001$, Fig. 5.4a) although no significant differences were found between the low and medium rates of clopyralid/picloram, clopyralid/triclopyr and fluroxypyr treatments ($P > 0.05$, Fig. 5.4a). Analysis of variance for the biomass of 6-, 9- and 12-month cohorts showed there was a significant effect of cohort ($F_{2,204} = 591.69$, $P < 0.0001$), treatment ($F_{18,204} = 591.69$, $P < 0.0001$) and a cohort × treatment interaction ($F_{36,204} = 591.69$, $P < 0.0001$) in which the oldest cohort was slightly differentially affected in the magnitude of herbicide effects (Figs. 5.4b-c).

Table 5.3. Median injury rating and mean rank ($\overline{\boldsymbol{R}}_{\boldsymbol{ij}}$) for treatment injury ratings for 3-, 6-, 9- and 12-month broom cohorts 179 days after treatment. Mean rank difference was separated for each broom cohort by column.

Treatment	*Median injury rating*				*Mean rank ($\overline{R}_{ij}$)*			
	3-mth	*6-mth*	*9-mth*	*12-mth*	*3-mth*	*6-mth*	*9-mth*	*12-mth*
clo/pic-L	7	7	9	8	33.3 bc	24.4 bc	44.0 abc	53.7 bc
clo/pic-M	9	10	10	7	48.1 abc	51.2 ab	52.8 abc	50.1 bc
clo/pic-H	10	10	10	9	67.0 a	52.2 ab	66.0 a	70.9 ab
clo/tric-L	6	10	10	7	31.4 bc	58.6 ab	51.4 abc	56.8 bc
clo/tric-M	10	10	10	9	52.8 abc	66.0 a	66.0 a	76.8 ab
clo/tric-H	10	10	10	10	51.9 abc	66.0 a	66.0 a	83.6 a
cpat-L	10	9	9	8	59.1 ab	45.8 abc	46.2 abc	58.1 bc
cpat -M	10	10	10	9	60.7 ab	59.6 ab	66.0 a	72.1 ab
cpat -H	10	10	10	9	67.0 a	66.0 a	66.0 a	73.4 ab
fluro-L	3	4	5	5	14.8 bcd	16.1 bc	16.9 bc	31.8 cd
fluro-M	3	6	5	5	19.2 bcd	28.8 abc	21.2 bc	26.2 cd
fluro-H	10	10	10	8	67.0 a	47.2 abc	66.0 a	57.1 bc
terbu-L	10	10	5	3	67.0 a	54.0 ab	31.4 bc	16.7 d
terbu-M	10	10	10	4	67.0 a	66.0 a	66.0 a	21.4 d
terbu-H	10	10	10	6	67.0 a	66.0 a	66.0 a	44.6 bcd
hexa-L	2	1	1	3	11.3 bcde	6.0 d	9.4 bc	9.9 d
hexa-M	10	10	1	3	57.2 abc	54.0 ab	29.8 bc	21.9 cd
hexa-H	10	10	10	10	67.0 a	66.0 a	66.0 a	75.6 ab
untreated	0	1	1	3	3.2 e	18.1 bc	12.2 bc	11.3 d

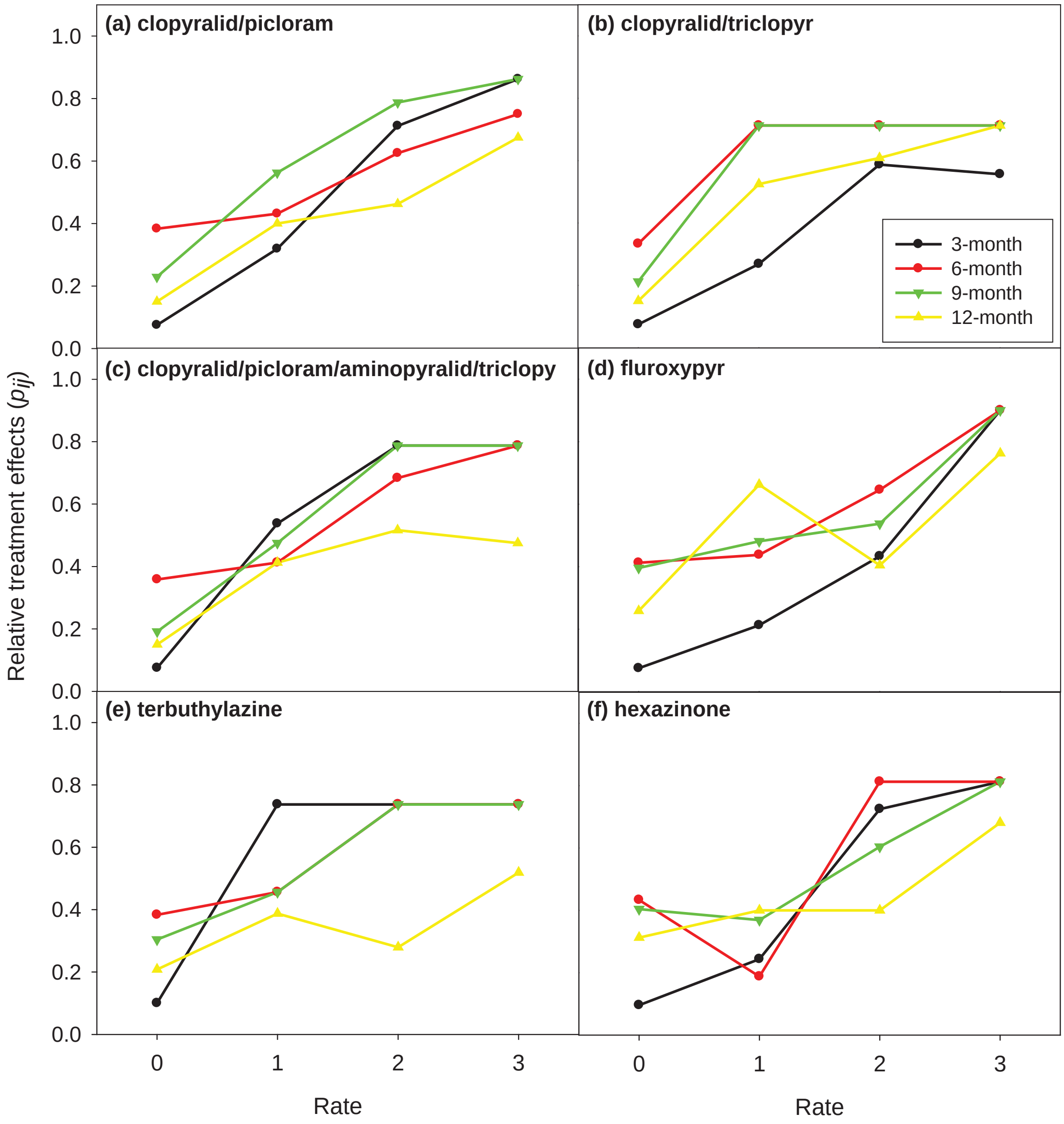


Figure 5.3. Estimated relative treatment effects ($\hat{p}_{ij}$) of 3-, 6-, 9- and 12-month broom cohorts applied with six herbicide ingredients at three spraying rates 179 days after treatments.

Table 5.4. Effects of broom cohorts (stages), herbicide rates and their interactions on injury ratings of broom 179 days after treatment. Bold values indicate statistically significant effects at $P < 0.05$.

Herbicide code	*Cohort*		*Rate*		*Cohort × Rate*	
	F^1	P	F	P	F	P
clo/pic	$2.29_{(2.21,9.26)}$	0.1536	$22.80_{(2.72,9.26)}$	**0.0002**	$0.88_{(4.7,9.26)}$	0.5228
clo/tric	$5.86_{(2.61,6.56)}$	**0.0302**	$24.11_{(2.87,6.56)}$	**0.0007**	$0.72_{(4.39,6.56)}$	0.6149
cpat	$2.87_{(2.4,4.65)}$	0.1527	$23.92_{(2.3,4.65)}$	**0.0033**	$1.04_{(3.38,4.65)}$	0.4646
fluro	$2.23_{(2.11,8.46)}$	0.1658	$17.65_{(2.29,8.46)}$	**0.0008**	$1.11_{(4.31,8.46)}$	0.4157
terbu	$2.96_{(2.4,4.75)}$	0.1442	$8.70_{(2.1,4.75)}$	**0.0254**	$1.05_{(3.83,4.75)}$	0.4673
hexa	$1.04_{(2.2,10)}$	0.3937	$19.01_{(2.51,10)}$	**0.0003**	$1.58_{(4.75,10)}$	0.2518

[1] Note: F test with degrees of freedom in the brackets

5.3.2 Effects of herbicides on **Pinus radiata**

Among the herbicides tested, phytotoxic effects on *P. radiata* were found with the fluroxypyr treatments when applied at medium and high rates with symptoms that were slightly visible between 98 and 179 DAT (Table 5.5). Differences in mean ranks and relative treatment effects did not differ between the treatments over time. Analysis of covariance on biomass with the initial height ($F_{1,4.1} = 19.84$, $P = 0.0106$) treated as covariate showed that treatments were significantly different ($F_{18,71.9} = 2.17$, $P = 0.0111$) (Fig. 5.4e).

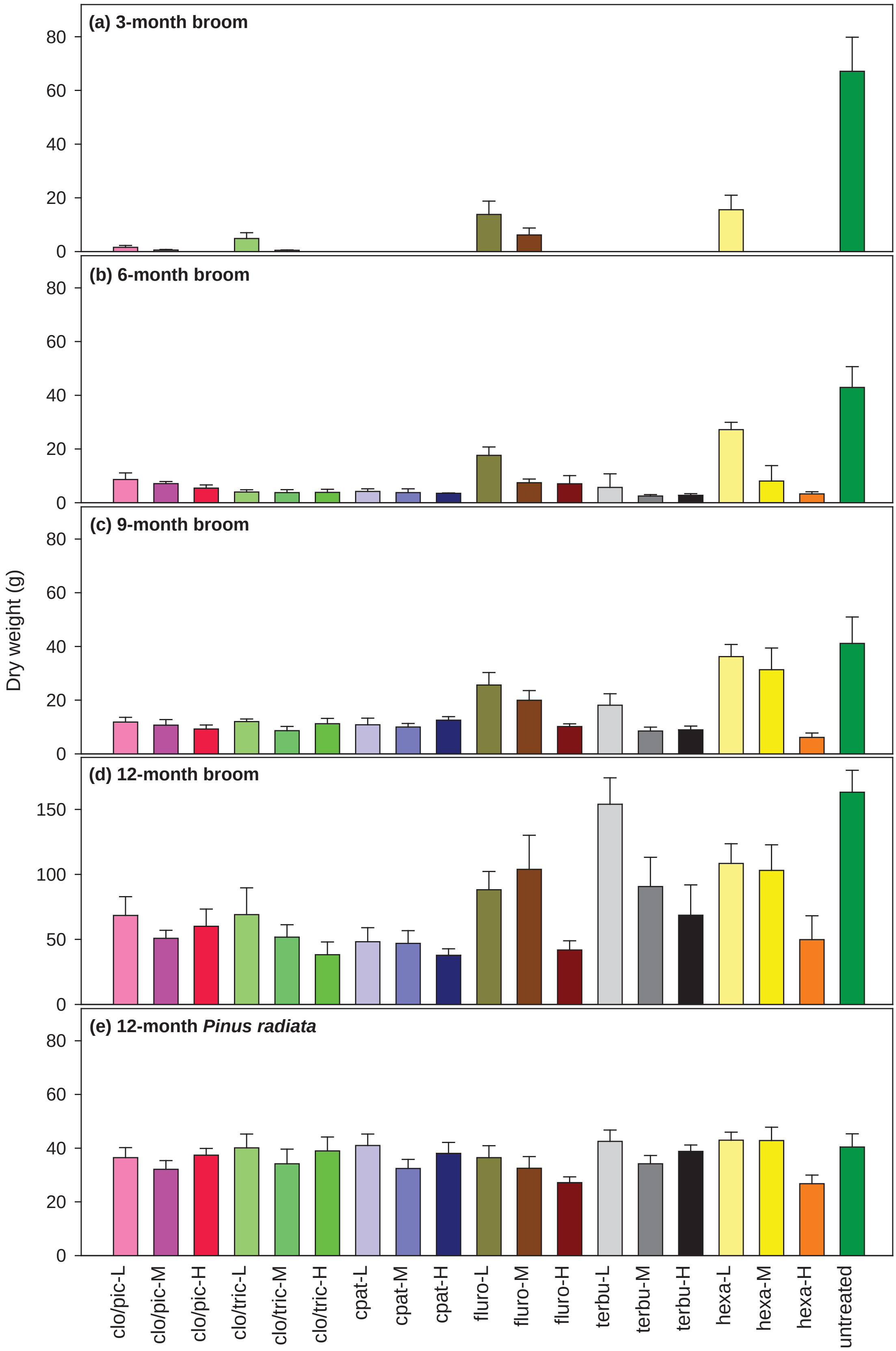


Figure 5.4. Mean (with standard error of the mean) dry weight (g) of 3, 6, 9 and 12-month-old broom cohorts and 12-month-old *Pinus radiata* 179 days after treatment.

Table 5.5. Median injury rating, mean rank ($\overline{\boldsymbol{R}}_{\boldsymbol{ij}}$) and relative marginal effects ($\hat{\boldsymbol{p}}_{\boldsymbol{ij}}$) along with standard errors (1SE) for treatment injury ratings for 12-month *Pinus radiata* 15, 98 and 179 days after treatment.

Treatment	*Median injury rating*			*Mean rank ($\overline{R}_{ij}$)*			*Relative marginal effects ($\hat{p}_{ij}$)*		
	15 DAT	*98 DAT*	*179 DAT*	*15 DAT*	*98 DAT*	*179 DAT*	*15 DAT*	*98 DAT*	*179 DAT*
clo/pic-L	1.0	1.0	1.0	157.3	157.3	182.1	0.55 (0.088)	0.55 (0.086)	0.64 (0.105)
clo/pic-M	1.0	1.0	1.0	132.5	132.5	132.5	0.46 (0.017)	0.46 (0.017)	0.46 (0.017)
clo/pic-H	1.0	1.0	1.0	132.5	132.5	157.3	0.46 (0.017)	0.46 (0.017)	0.55 (0.087)
clo/tric-L	1.0	1.0	1.0	108.3	132.5	157.3	0.38 (0.084)	0.46 (0.017)	0.55 (0.086)
clo/tric-M	1.0	1.0	1.0	132.5	132.5	157.3	0.46 (0.017)	0.46 (0.017)	0.55 (0.087)
clo/tric-H	1.0	1.0	1.0	132.5	133.1	108.3	0.46 (0.017)	0.47 (0.133)	0.38 (0.082)
cpat-L	1.0	1.0	1.0	132.5	84.1	84.1	0.46 (0.017)	0.29 (0.101)	0.29 (0.101)
cpat -M	1.0	1.0	1.0	132.5	157.3	182.1	0.46 (0.017)	0.55 (0.085)	0.64 (0.104)
cpat -H	1.0	1.0	1.0	132.5	136.2	161.0	0.46 (0.017)	0.48 (0.141)	0.56 (0.163)
fluro-L	1.0	1.0	1.0	133.1	157.3	157.3	0.47 (0.132)	0.55 (0.083)	0.55 (0.083)
fluro-M	1.0	6.0	4.0	132.5	222.6	194.6	0.46 (0.017)	0.78 (0.183)	0.68 (0.183)
fluro-H	1.0	5.0	2.0	157.3	274.9	216.7	0.55 (0.086)	0.96 (0.015)	0.76 (0.119)
terbu-L	1.0	1.0	1.0	108.3	108.3	108.3	0.38 (0.085)	0.38 (0.083)	0.38 (0.083)
terbu-M	1.0	1.0	1.0	132.5	157.3	157.3	0.46 (0.017)	0.55 (0.087)	0.55 (0.087)
terbu-H	1.0	1.0	1.0	132.5	108.3	108.3	0.46 (0.017)	0.38 (0.083)	0.38 (0.083)
hexa-L	1.0	1.0	1.0	108.3	132.5	132.5	0.38 (0.085)	0.46 (0.017)	0.46 (0.017)
hexa-M	1.0	1.0	1.0	108.3	157.3	132.5	0.38 (0.084)	0.55 (0.086)	0.46 (0.017)
hexa-H	1.0	1.0	2.0	157.3	182.1	210.0	0.55 (0.087)	0.64 (0.106)	0.74 (0.110)
untreated	1.0	1.0	1.0	108.3	133.0	108.3	0.38 (0.081)	0.47 (0.132)	0.38 (0.081)

5.4 Discussion

The effects of selective herbicides assessed in this trial were to simulate the situation occurring in *P. radiata* sites when control of broom of various ages is attempted. When the sites are cleared prior to planting trees, the dormancy of some of the broom seed bank breaks, and broom seedlings inevitably will establish among the newly planted trees. In this study, the effects of herbicides available for selectively removing this broom were compared for broom plants at different stages of development, and their safety on young pines was also compared. The visual effects of herbicides on broom were visible soon after the treatment application (15 DAT), but slightly changed over the course of the experiment for some of the herbicides. There was no mortality of *P. radiata* for any of the herbicides and rates tested but there were some phytotoxic effects noted.

Excellent broom control was obtained using the recommended rates of the clopyralid/triclopyr mixture and the clopyralid/triclopyr/picloram/aminopyralid mixture, though both treatments did not quite give 100% control of the youngest (three months old) and the oldest (12 months old) cohorts of broom. The clopyralid/picloram mixture also gave good control, although was not as effective as the above two mixtures. Clopyralid is more persistent in plant tissue than naturally occurring auxins and the binding causes abnormal growth leading to plant death in a few days or weeks, depending on the species (Cox 1998). Triclopyr causes the growing tips of the plant to elongate, followed by distortion, withering, and the death of the plant (Cox 2000) and it effectively controls certain woody plants and perennial weeds (Bovey *et al.* 1979). Moffat (1966) showed that picloram applied at 1680 g a.i. ha^{-1} in October, when broom was actively growing and flowering had commenced, successfully controlled broom. Results of herbicide mixes from my study are comparable with a trial testing a mix of clopyralid (1500 g a.i. ha^{-1}), triclopyr (150 g a.i. ha^{-1}) and picloram (50 g a.i. ha^{-1}) and a mix of haloxyfop (250 g a.i. ha^{-1}), clopyralid (1500 g a.i. ha^{-1}), triclopyr (150 g a.i. ha^{-1}) and picloram (50 g a.i. ha^{-1}), both of which showed nearly 100% mortality of four month old broom (Rolando *et al.* 2011a).

Terbuthylazine gave excellent control of broom up to nine months old for both the standard and high rates, but the oldest broom was quite tolerant. The lower rate however only caused 100% broom mortality up to six month old. Hexazinone caused 100%

broom mortality up to six months old at the standard rate and up to 12 months old at the highest rate, but the lower rate was not was not as effective as terbuthylazine. All of these herbicides caused no significant damage to *P. radiata*, even at double the recommended rates (apart from double the recommended hexazinone rate) which was similar to the results from Rolando *et al.* (2011a). The effects of two formulation of hexazinone at two rates (1000 and 1500 g a.i. ha^{-1}) with two application methods (1.5 m wide strip and total area) tested on a 1-year-old *P. radiata* stand in South Africa also indicated that these rates were safe to pine trees and suppressed weeds three years after application (Gous 1996a). In another study, hexazinone applied at 1500 and 2000 g a.i. ha^{-1} during summer in South Africa had no detrimental effect on *P. radiata* when applied over the foliage and actually improved their height growth (Gous 1997). Similar results were found when hexazinone was applied even at lower rates (560 and 1120 g a.i. ha^{-1}) on longleaf pine seedling (*Pinus palustris* Mill.) over two years (Ramsey & Jose 2004). Overall, the rates used in my trial were much higher than those used in these studies.

With regard to the toxicity of herbicides, only fluroxypyr showed visible phytotoxicity on *P. radiata*. Fluroxypyr is not registered for use in *P. radiata*, but was evaluated since it is closely related to triclopyr and, thus, might have given useful activity on broom while still being safe for pines. Epinasty was observed in the treated *P. radiata* plants. This symptom is most characteristic of herbicides such as 2,4-D, dicamba, triclopyr, clopyralid, aminopyralid and picloram that interfere with hormonal regulation in plants (Radosevich *et al.* 2007). Fluroxypyr is commonly used for the selective control of broadleaf weeds in cereals (Macdonald *et al.* 1994). Hannan (1998) reported that fluroxypyr applied at 4560 g a.i. ha^{-1} in summer killed more than 90% of *Lantana camara*, a weedy perennial shrub. In my study, although the highest rate used (900 g a.i. ha^{-1}) gave good control of broom, lower rates performed poorly. However, the damage caused to *P. radiata* at standard and high rates up to 98 DAT (Table 5.5; Fig. 5.2e) was considered too great for this chemical to be considered further. The main symptom found was apical damage and twisting of stems.

Rolando *et al.* (2011a) also recognised tip damage to *P. radiata* caused by several herbicide treatments 30 DAT, but this was not significant at 90 DAT. Previous research has shown that the season of application plays a vital role in herbicide efficacy.

Hexazinone applied at 900 g a.i. ha^{-1} in spring caused burning of *P. radiata* (Harrington 1993). However, an application of hexazinone at 2000 g a.i. ha^{-1} in summer caused no damage to *P. radiata* (Donald 1986). The visible damage caused to *P. radiata* in trials by Rolando *et al.* (2011a) could be explained by application timing (spring), whereas my trial was applied in summer. These results, however, need to be confirmed by field trials.

If grass ground covers were to be planted with *P. radiata*, the treatments using clopyralid, triclopyr, picloram and aminopyralid would allow safe removal of broom from the developing ground covers, without harming grasses. These grasses might then be able to out-compete any further broom seedlings (see Chapter 3). In the previous chapter, I evaluated the residues of these various herbicides on broom seedings. In the next trial (described in Chapter 6), the effects of combination of herbicides and grass competition were investigated.

A summary of cost analysis (Table 5.6) used in my trial indicated that hexazinone is not a suitable treatment as it is the most costly herbicide (\$880 ha^{-1} at the standard rate) and is only effective for controlling broom up to six month old at the standard rate. Terbuthylazine is cheaper (\$231 ha^{-1}at the standard rate) and successfully killed broom up to nine months of age, but as with hexazinone would be very damaging to ground cover species. Another option might be the use of standard rates of clopyralid/triclopyr (\$275.4 ha^{-1}) or clopyralid/picloram/ aminopyralid/triclopyr (\$295 ha^{-1}) to get more successful control broom up to nine months old which is cheaper than using hexazinone at the same rate (\$880 ha^{-1}). These figures, however, only show the costs of herbicides used only without costs for application and surfactants.

Table 5.6. Cost analysis for herbicide treatments used in the trial.

No	*Active ingredient (rate, g a.i. ha^{-1})*	*Trade name (rate)*	*[1]Cost ($ ha^{-1})*
1	clopyralid/picloram (225/150)	Radiate (1 L ha^{-1})	103.8
2	clopyralid/picloram (450/300)	Radiate (2 L ha^{-1})	207.6
3	clopyralid/picloram (900/600)	Radiate (4 L ha^{-1})	415.3
4	clopyralid/triclopyr (750/150)	Versatill/Grazon (2.5/0.25 L ha^{-1})	137.7
5	clopyralid/triclopyr (1500/300)	Versatill/Grazon (5/0.5 L ha^{-1})	275.4
6	clopyralid/triclopyr (3000/600)	Versatill/Grazon (10/1 L ha^{-1})	550.7
7	clopyralid/picloram/aminopyralid/triclopyr (750/25/2/75)	Versatill/Tordon Brushkiller XT (2.5/0.25 L ha^{-1})	147.5
8	clopyralid/picloram/aminopyralid/triclopyr (1500/50/4/150)	Versatill/Tordon Brushkiller XT (5/0.5 L ha^{-1})	295.0
9	clopyralid/picloram/aminopyralid/triclopyr (3000/100/8/300)	Versatill/Tordon Brushkiller XT (10/1 L ha^{-1})	590.0
10	fluroxypyr (250)	Starane (1.25 L ha^{-1})	51.3
11	fluroxypyr (500)	Starane (2.5 L ha^{-1})	102.7
12	fluroxypyr (1000)	Starane (5 L ha^{-1})	205.3
13	terbuthylazine (5000)	Gardoprim (10 L ha^{-1})	115.5
14	terbuthylazine (10000)	Gardoprim (20 L ha^{-1})	231.0
15	terbuthylazine (20000)	Gardoprim (40 L ha^{-1})	462.0
16	hexazinone (3000)	Velpar DF (4 kg ha^{-1})	440.0
17	hexazinone (6000)	Velpar DF (8 kg ha^{-1})	880.0
18	hexazinone (12000)	Velpar DF (16 kg ha^{-1})	1760.0

[1] Source: Askin, D. and Askin, V. (2012). Financial Budget Manual 2012/3. Faculty of Commerce, Lincoln University, Lincoln, New Zealand

[1] Costs (NZD) shown here are GST exclusive: Radiate ($519.13 5 L^{-1}); Versatill ($1037.39 20 L^{-1}); Grazon ($640 20 L^{-1}); Tordon Brushkiller XT ($356.52 5 L^{-1}); Starane ($205.30 5 L^{-1}); Gardoprim ($231 20 L^{-1}) and Velpar DF ($1100 10 kg^{-1}).

5.5 Implications for management and future research

The results from this trial indicates that broom can be selectively removed from pines during the first nine months of growth using herbicide mixtures based on clopyralid and triclopyr, clopyralid and picloram, or terbuthylazine. As this work only used potted plants, the herbicide combinations and rates used need to be further tested in field trials to confirm efficacy on broom and safety on young pines.

CHAPTER 6
POPULATION DYNAMICS OF BROOM (*Cytisus scoparius*) UNDER VARIOUS MANAGEMENT SCHEMES IN A RADIATA PINE (*Pinus radiata*) PLANTATION

6.1 Introduction

Invasive plants are one of the leading threats to biological diversity in natural and managed areas (Mack *et al.* 2000) due to their long lasting and pervasive effects (Coblentz 1990). Understanding the dynamics of invasive plant species therefore is important for management strategies. Ecologists are increasingly asked to forecast how populations will respond to anthropogenic environmental changes such as habitat loss or climate change or to management actions such as control of invasive species (Heppell *et al.* 2000; Crone *et al.* 2013). Modelling provides an important tool for exploring the consequences of different management strategies (Buckley *et al.* 2003b). Two main strategies are normally used to evaluate control strategies based on population models. The first strategy is to use perturbation analyses (sensitivity and/or elasticity analysis) to identify the life-history stages having the greatest impact on population growth rates and, therefore, the most appropriate stages to target for control. Population models based on difference equations (Rees & Paynter 1997; Rees & Hill 2001) and matrix models (Shea & Kelly 1998; Parker 2000; Magda *et al.* 2009) have been used for this purpose. The second strategy used is to develop models that enable the direct evaluation of management impacts on target population dynamics (Shea & Kelly 1998; Higgins *et al.* 2000; Buckley *et al.* 2001; da Silveira Pontes *et al.* 2012). Matrix projection models are the primary tools used to study plant and animal population dynamics (Morris & Doak 2002; Crone *et al.* 2011). Quantifying the effects of different life stages or life history processes on the rate of growth of a population is a principal aim of demography (Morris & Doak 2005). These effects are typically measured by the so-called ‘‘sensitivities’’ of the population growth rate or by related quantities termed ‘‘elasticities’’ both of which can be calculated from population projection matrices (Caswell 2001).

Management of weeds and invasive plants is a strategy that generally includes a combination of approaches of prevention, eradication, and control, of which the latter is normally used reduce or suppress weeds in a defined area without nesssarily elimilating them (Radosevich *et al.* 2007). To be sucessfully controlled, weeds are to be managed by using a combination of physical, cultural, biological and chemical methods. Although integrated weed management (IWM) strategies are being widely used to control invasive plants (Herrera-Reddy *et al.* 2012), there is not much research on the effectiveness of IWM for invasive plants (Ainsworth 2003; Vitelli & Pitt 2006). Some success has been reported using biological control and herbicides to manage leafy spurge (*Euphorbia esula*) (Lym 2005), purple loosestrife (*Lythrum salicaria*) (Henne *et al.* 2005), and Canada thistle (*Cirsium arvense*) (Collier *et al.* 2007). The success of integrated management should be assessed using multiple dimensions of biological, ecological, scientific, social, economic, political and legal aspects (Anderson *et al.* 2000).

Broom is a persistent species due to its large seed bank and long-lasting seed viability beneath broom stands. However, it is likely that the seed bank density differs among the sites and under different *P. radiata* stands reflecting differences in management and invasion history (see Chapter 2). Broom has been the subject of a number of modelling studies discussed in Chapter 1 (Section 1.2.8) which applied prospective approaches to evaluate management strategies before they are implemented. Moreover, these models are mainly concerned with targeting key stages that are important for broom pollination (bumblebees), biological control and grazing in scrublands and grasslands, which may not be able to be used to predict the outcomes of forest management strategies on broom invasion in plantation forests. In the previous chapters, applications of ground covers and herbicides have been separately tested to assess their capability on controlling broom during pre- and post-plant stages of forest management. The results obtained from these studies are important for finding suitable cost effective and environmentally-friendly control options for broom in plantation forests.

In this study, a combined method using matrix population models was used to assess the effects of control strategies (herbicides and ground covers) to predict key target stages for future control of broom.

6.2 A conceptual model for broom in New Zealand

Based on the results of the previous models of broom, a conceptual model for broom in New Zealand was developed in order to evaluate potential management options on changes in broom population dynamics (Fig. 6.1). This model was used to try to predict and understand the likely outcomes of different management options.

6.3 Objectives

This study was conducted to: (1) quantify the changes in broom populations at the sites where *P. radiata* has been planted, (2) identify factors affecting germination and establishment of broom over time under various management schemes and (3) assess the likely efficacy of various management schemes (herbicides and ground covers) on survival within and transitions between broom life stages (seeds, seedlings, juveniles and adults) in a newly planted *P. radiata* stand using matrix population models.

6.4 Research questions and hypotheses

Specific research questions and/or hypotheses were addressed through this research, including the following:

1. Does germination of broom exhibit temporal variability? Is seedling emergence affected by herbicides and/or grass covers? Is there a relationship between spraying and broom seedling establishment and survival?
2. Is the combined effects of grass cover and herbicide applications on the time taken for seedlings to establish and on the subsequent growth rate additive or multiplicative? How is seedling survival and transitions to more advanced life-stages dependent on the degree of drought, herbivory and grass and/or herbicide suppression?
3. Which treatments and/or combinations of treatments (grasses and herbicides) are most effective at controlling established broom plants and limiting the germination of broom seedlings while minimising the adverse effects on the growth of pine trees?

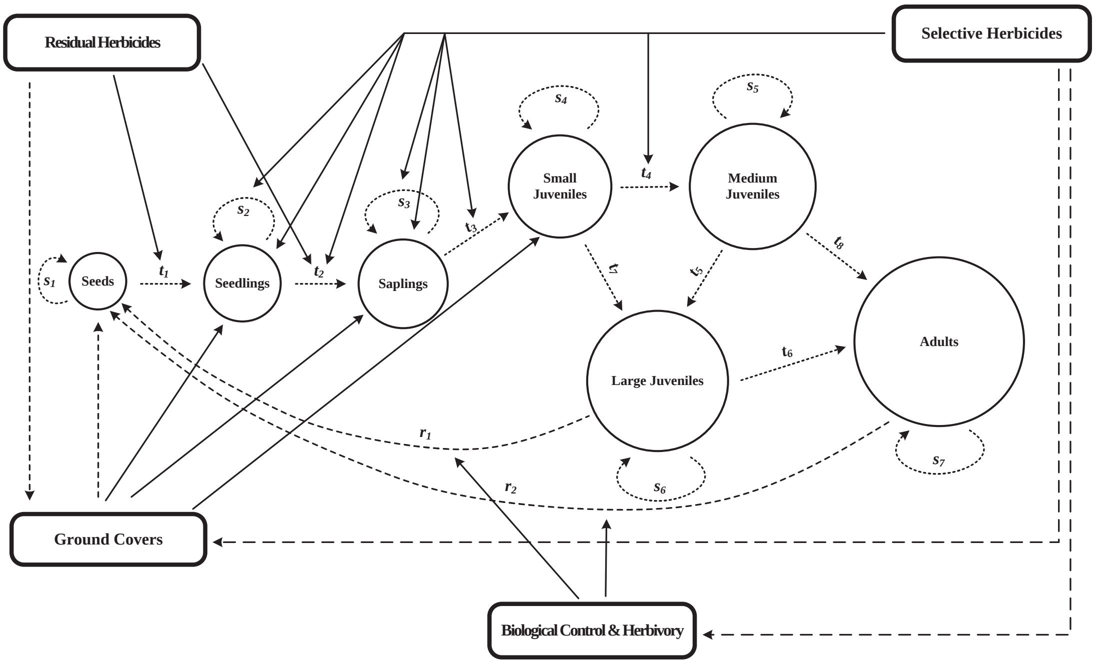


Figure 6.1. A **c**onceptual model showing the effects of some potential management regimes on broom transitional probability. The solid arrows show the direct effects of control measures on some of the life stages. Indirect effects between control methods are illustrated by thick, dashed arrows. Transitions between stages are indicated by narrow, dashed arrows: s_i is the probability of surviving and staying in state i, t_i is the probability of surviving and growing from stage i to stage $i + 1$ and r_i is the possibility of reproductive transitions.

6.5 Materials and methods

6.5.1 Study site

The study area was located at a *P. radiata* forest (Compartment No. 255.02 of Gwavas Forest) in Hawke's Bay, New Zealand (Fig. 6.2). The soil was a Ruahine silt loam and samples taken from the trial site had an average pH of 5.7. Olsen-P was measured at 2 μg mL^{-1} and the Na, Mg, K and Ca levels averaged 0.11, 0.63, 0.26 and 3.5 me 100 g^{-1}, respectively. Soil organic matter averaged 13.0% and average CEC of 17 me 100 g^{-1}.

Climate data for the study site (Fig. 6.3) were collected daily from the Gwavas Forest Centre located approximately 10 km away.

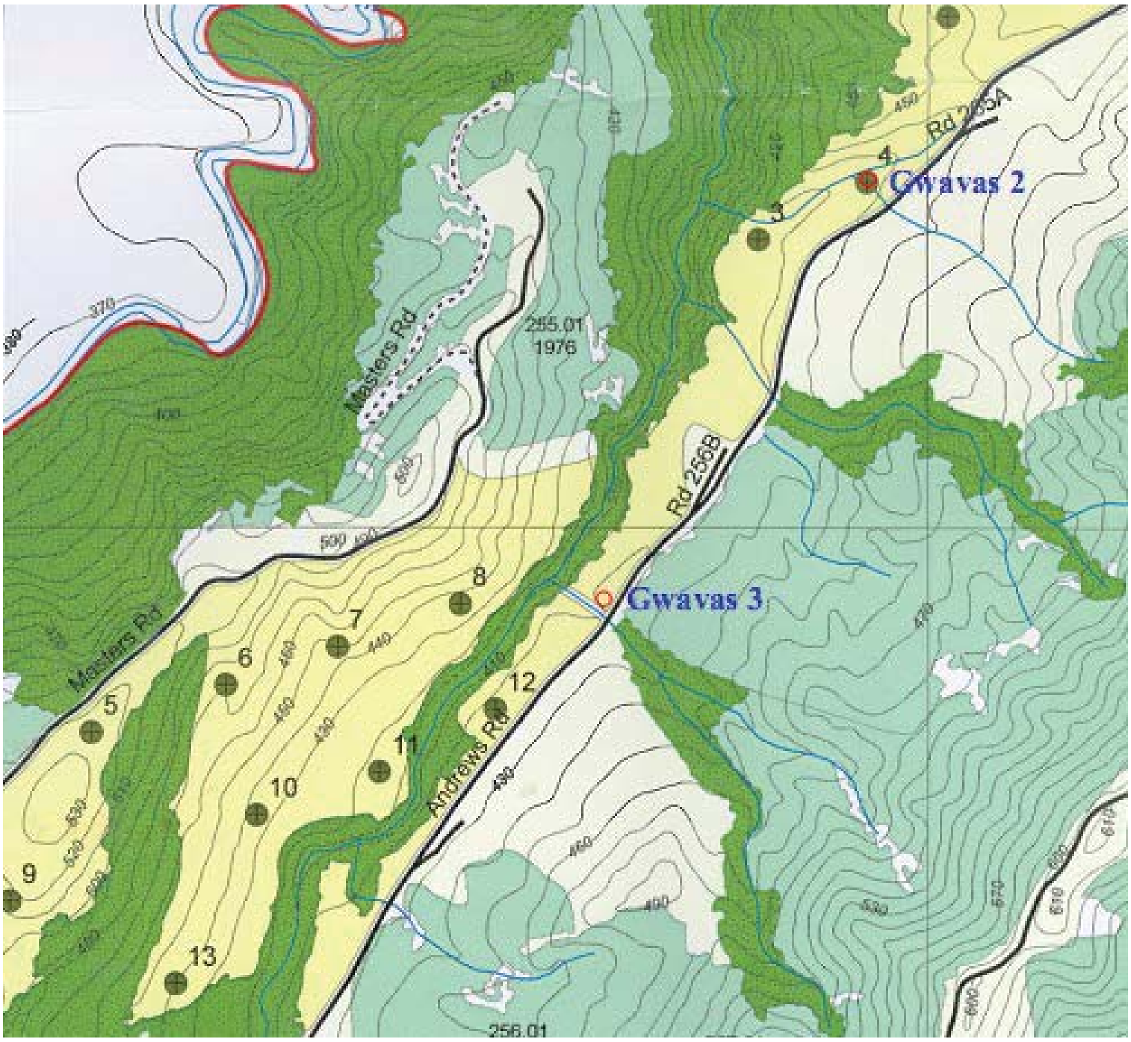


Figure 6.2. Map of Gwavas forest showing two sampling locations (Gwavas 2 and Gwavas 3) within a newly planted *Pinus radiata* stand (see the text for details).

The site (Gwavas 3; Fig. 6.2) was aerially sprayed on 26 February 2009 with a mixture of Agpro Green Glyphosate 510 at 5 L ha^{-1} (equivalent to 2.55 kg a.i. ha^{-1} glyphosate), Agpro Meturon at 100 g ha^{-1} (60 g a.i. ha^{-1} metsulfuron-methyl) and an organosilicone surfactant (Agpro Organosilicone at 0.5 L ha^{-1}) in 100 L water ha^{-1}. The site was then aerially oversown with a coated mixture of Yorkshire fog (*Holcus lanatus* L.) (7 kg ha^{-1}) and lotus (*Lotus pedunculatus* Cav.) (2 kg ha^{-1}) in May 2009. The site was planted with *P. radiata* seedlings (40 cm in height and 5 mm in diameter at the base) on 28 May 2009 at the spacing of 5 × 2.4 m (833 stems ha^{-1}) within three rows separated by windrows. Due to the number of seedlings that died in the first year, the site was replanted on 25 May 2010 with a further 100 *P. radiata* seedlings (see Section 6.6 for details).

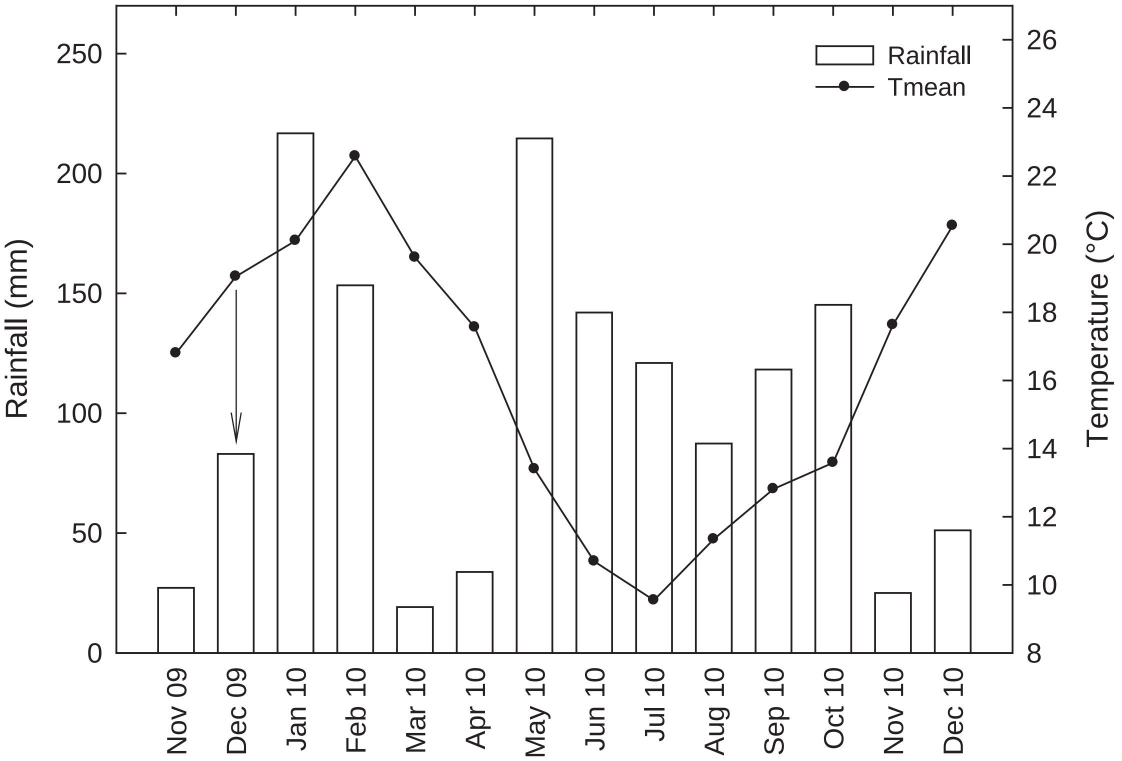


Figure 6.3. Mean total monthly rainfall (mm) and mean monthly temperature (°C) over the duration of the experiment. The arrow shows the time when the experiment started in December 2009.

6.5.2 Broom seed bank sampling

Before the start of the experiments, a preliminary survey of the broom seed bank and *P. radiata* compartment characteristics was conducted on 14 July 2009 in two compartments: Compartment 1 (Gwavas 1) which was due to be planted in 2010 and Compartment 2 (Gwavas 2 and Gwavas 3 in Fig. 6.2) which was subsequently planted in May–June 2009. Soil samples were taken using a soil core sampler (3 cm in diameter and 40 cm in length which was similar to the one used for seed bank sampling at the Tree Farm forest in Chapter 2) to a depth of 10 cm with four soil cores taken from corners of 1m^2 (1 × 1 m) plots and one core at the centre of each plot. Plots selected at random were used for sampling in each compartment. Four plots were used inside the Compartment 1 (Gwavas 1) and three plots located in each of two areas in the Compartment 2, i.e. Gwavas 2 and Gwavas 3. The five cores from each plot were pooled together, kept in a plastic bag and then stored in a cool room (5°C) before being analysed. The broom seeds were extracted after being sieved through a 1.0 mm mesh to remove other materials (stones, roots, etc.). Preliminary results showed that there was no seed found at Compartment 1 while the seed density varied approximately from 380 (Gwavas 2) to 18,000 seeds m^{-2} (Gwavas 3) in Compartment 2.

The seeds collected were assessed for their viability with germination tests on 17 July 2009 using the same method for seeds collected from the Tree Farm forest (Chapter 2). Results after 28 days indicated that 99% of scarified seeds were viable. This information was used for calculating seed bank survival as part of developing matrix population models (see Section 6.5.5.3)

6.5.3 Experimental design

The efficacy of different herbicides with/without ground covers to effectively remove established broom plants and limit germination of broom seedlings was explored using a randomised block design with four blocks and density of voluntary and/or sown grasses used as a criterion to allocate plots to blocks. Treatments were randomly allocated in each of the blocks and the following herbicides were applied on 9 December 2009 (see Table 6.1 for more details):

1. *terbuthylazine/hexazinone whole plots* (8 plots × 4 quadrats)

    Whole-plot sprayed with terbuthylazine/hexazinone (8500/1500 g a.i. ha^{-1}).

2. *terbuthylazine/hexazinone spots* (4 plots × 4 quadrats)

    terbuthylazine/hexazinone (8500/1500 g a.i. ha^{-1}) spot sprayed (1.5 m in diameter) around pine trees.

3. *Grass-free spots/broom-free whole plots* (4 plots × 8 quadrats)

    - haloxyfop (250 g a.i. ha^{-1}) spot sprayed (1.5 m in diameter) around pine trees.
    - Whole-plot sprayed with clopyralid (1125 g a.i. ha^{-1}) + triclopyr/picloram/aminopyralid (112.5/37.5/3 g a.i. ha^{-1}) + organosilicone (400 g a.i. ha^{-1}).

4. *Grass/broom-free spots* (4 plots × 4 quadrats)

    Spot sprayed (1.5 m in diameter) with haloxyfop (250 g a.i. ha^{-1}) and clopyralid (1125 g a.i. ha^{-1}) triclopyr/picloram/aminopyralid (112.5/37.5/3 g a.i. ha^{-1}) + organosilicone (400 g a.i. ha^{-1}).

5. *No herbicides* (4 plots × 4 quadrats)

    Voluntary and/or sown grasses with no herbicides applied.

Before applying the treatments, all the grasses present were evaluated and recorded (species, cover percentages and heights) using visual assessments. Data on percentage broom cover were also recorded and used as a covariate to allocate the treatments into plots. Each main plot included 10 pine trees selected for taking measurements (5 trees × 2 rows) nested in an area of 100 m^2 (12.6 × 8 m) and separated from each other by a two-row buffer of untreated trees to prevent contamination from drift of herbicides used in adjacent plots (Fig. 6.4). The total area receiving spot spraying treatments (1.5 m in diameter) in the Treatments 2 and 4 was 142 m^2 (1.77 m^2 × 10 pine trees × 2 treatments × 4 blocks). The corners of each treatment plot were marked using white rods approximately 1 m tall. Broom seed density in each plot was evaluated on 4 December 2009 by taking soil samples using a subplot sized 1 m^2 (1 × 1 m) with four soil cores (3 cm in diameter and 10 cm in depth) taken from the corners and one core at the centre of the plot. Two subplots in each of the main plots in Fig. 6.4 placed in between the two rows and between the Trees 2 and 9 (subplot 1) and the Trees 4 and 7 (subplot 2) were used for sampling (10 cores in total).

Table 6.1. Treatments applied in Gwavas forest.

No.	[1]*Treatment*	*Active ingredient (rate, g a.i. ha^{-1})*	*Trade name (rate, L ha^{-1})*
1	Whole plot	terbuthylazine/hexazinone (8500/1500)	Valzine 500 (20 L ha^{-1})
2	Spot	haloxyfop/terbuthylazine/hexazinone (250/8500/1500)	Gallant NF/Valzine 500 (2.5/20)
3	Whole plot	clopyralid/triclopyr/picloram/aminopyralid/organosilicone (1125/112.5/37.5/3/400)	Versatill/Tordon Brushkiller XT/Pulse (3.75/0.375/0.5)
4	Spot	haloxyfop/clopyralid/triclopyr/picloram/aminopyralid/organosilicone (250/1125/112.5/37.5/3/400)	Gallant NF/Versatill/Tordon Brushkiller XT/Pulse (2.5/3.75/0.375/0.5)
5	No herbicides	NA	NA

[1]Note: Spot spray treatments (1.5 m in diameter) were applied around *Pinus radiata* trees.

This one-year experiment was part of a larger trial that was continued by Scion (New Zealand Forest Research Institute Limited) in the second year. Each treatment consisted of four plots (with the exception of Treatment 1 which included eight plots) in which sampling quadrats were positioned (see next Section). From these plots, four zones were recognised in which the broom subjected to the same regime:

Zone A (all vegetation killed initially with terbuthylazine/hexazinone – "all vegetation cleared"): 48 quadrats (4 quadrats × 8 plots + 4 quadrats × 4 plots) from Treatments 1 and 2, respectively).

Zone B (broom killed initially with clopyralid/triclopyr/picloram and grasses killed with haloxyfop but not the other weeds – "broom and grass cleared"): 32 quadrats (4 quadrats × 4 plots + 4 quadrats × 4 plots) from the spot sprays from Treatments 3 and 4.

Zone C (broom killed initially with clopyralid/triclopyr/picloram and grasses kept intact – "broom cleared"): the remaining parts of Treatment 3 with 16 quadrats (4 quadrats × 4 plots).

Zone D (no herbicides): 48 quadrats from Treatment 5 (4 quadrats × 4 plots) + Treatment 2 (4 quadrats × 4 plots) + Treatment 4 (4 quadrats × 4 plots).

6.5.4 Data collection and measurements

Assessments on broom (seedling and sapling density and cover percentage), cover percentage of botanical composition and debris in each treatment plot were carried out before the treatments applied and at 4-month intervals after the treatment applications for a year. Treatments 1, 3 and 5 included four quadrats, of which two quadrats were placed beside the Trees 2 and 7 and the other two quadrats placed at 1.5 m apart from the Trees 4 and 9 within the plot, resulting in 48 quadrats to be measured (4 quadrats × 3 treatment plots × 12 blocks) (Fig. 6.4). Treatments 2 and 4 consisted of four pairs of quadrats placed at the Trees 2, 4, 7 and 9, of which one quadrat was placed within 0.75 m radius surrounding each pine plant and another setup outside the spray spot at 1.5 m from the pine tree, resulting in 64 quadrats to be measured (8 quadrats × 2 treatment plots × 4 blocks) (Fig. 6.4).

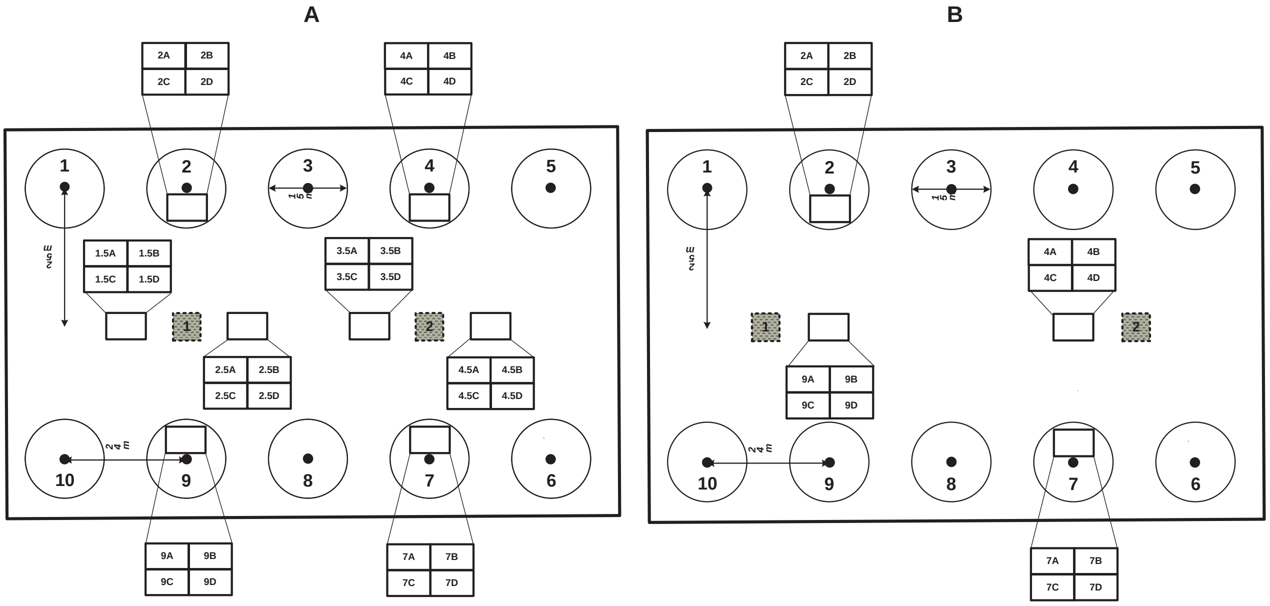


Figure 6.4. Layout of two experimental plots showing sampling quadrats within (A) the spot spray with eight quadrats and (B) whole-plot spray/untreated control with four quadrats randomly nested within each plot. (A) Four quadrats were setup within the 1.5 m diameter of the pine trees 2, 4, 7 and 9; and other four were at the middle of the plot in between the trees 1, 2, 3, 4 and 5. (B) Two quadrats were setup within the 1.5 m diameter of the pine trees 2 and 7; and other two were at the middle of the plot next to the trees 4 and 9. Additional two plots (dotted) were used for broom seed bank sampling in each main plot (see the text for details).

A series of 0.25 m^2 (0.6 × 0.42 m) quadrats (four A4 acetate sheets) laid inside each plot was used for monitoring broom and grasses in each plot and the number of quadrats to be used varied based on treatments. The quadrat was marked using two fibreglass electric fence rods (cut in half) placed in the diagonal corners of the quadrat. The surviving broom seedlings and plants were marked and counted and their heights, diameters at the base and growth forms recorded as they changed to other stages (see Table 6.2 for details). In each plot, the location of each broom seedling was recorded using four A4-sized acetate sheets arranged on a mapping table to assess their survival. Live broom plants (approximately 10 cm in height or more) were tagged, counted and their heights and diameters at the base and growth forms subsequently recorded. The monitoring scheme used for each quadrat depended on the number of broom seedlings appearing on each acetate sheet (see Fig. 6.5 for details). The plant age at which flowering first occurred and the minimum plant height and crown diameter at flowering were also recorded for the tagged plants. Grasses were assessed separately depending on the species, and percent cover of the species using visual estimates and the average height of main grass species was determined at time of monitoring. Photos representing typical broom plants were taken at each measurement time.

Table 6.2. Criteria for classifying broom individuals into seven stages for building matrix population models

[1]*Stage*	*Cotyledons/leaves present*	*Branches present*	*Reproduction*	*Height (cm)*
Seed (S)	–	–	–	–
Seedling (SL)	Yes	No	No	–
Sapling (SP)	No	Yes	No	< 10
Small juvenile (SJ)	No	Yes	No	> 10, < 20
Medium juvenile (MJ)	No	Yes	No	> 20, < 40
Large juvenile (LJ)	No	Yes	Yes	> 40, < 80
Adult (AD)	No	Yes	Yes	> 80

[1] The criteria were based on the stage transitions of broom in the field conditions. The transition from one stage to the next was evaluated based on the sequence of each criterion. The transitions between (1) seed and seedling and (2) seedling and sapling may vary and therefore height was not used in this case. Seedlings were classified as having cotyledons and saplings having branches but less than 10 cm in height. The transition between large juvenile and adult is of importance as at these stages, broom is able to flower and set seeds.

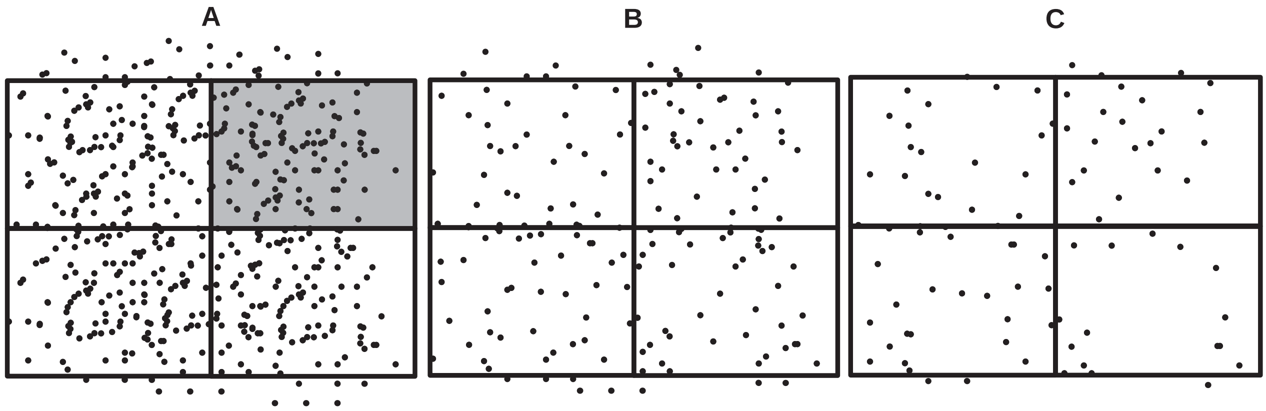


Figure 6.5. The three monitoring schemes used for the quadrats (0.25 m^2) consisting of four acetate sheets placed on a mapping table on which broom seedlings and saplings were mapped. (A) If the number of broom seedlings and plants were consistently spaced across all planned sheets, i.e. >100 seedlings per sheet, broom plants were marked from just one acetate sheet (grey area in this case) was used for the analysis. (B) If the number of broom of seedlings and plants was high but followed a clumped or uneven pattern, half of each of the sheets was used for marking the broom seedlings and the information in all four sheets was combined for the analysis. (C) If the number of broom seedlings and plants was low, all four sheets were used.

6.5.5. Data analysis

All statistical analyses were conducted using SAS 9.2 (SAS Institute Inc. 2008) and R 3.0.1 (R Core Team 2013) software. Treatment effects were considered significant at $P < 0.05$ for all analyses.

6.5.5.1 Broom seedling emergence and survival

Data on broom seed bank and seedling emergence before herbicide treatments were analysed. Preliminary analyses of residuals performed on seedling and sapling emergence before the treatments using PROC UNIVARIATE revealed a skewed error distribution. So, generalized linear mixed models were fitted to the seedling emergence data using PROC GLIMMIX (Willenborg *et al.* 2005; Harrison *et al.* 2007; Fedriani & Delibes 2009) with Poisson error terms (O'Hara & Kotze 2010) with "seed bank" and "emergence" within each zone as fixed effects, and the quadrats and quadrats nested within plots × zones treated as random effects. Tukey's honestly significant difference (HSD) tests were then used to perform multiple comparisons between all pairs of treatments when ANOVA results indicated significant treatment effects.

Data on the emergence and survival of broom seedlings (regardless of their subsequent transitions after the herbicide treatments analysed were applied) were initially attempted to be analysed with PROC GLIMMIX but the analysis failed due to lack of convergence during the runs. The lack of convergence was due to the large number of quadrats that exhibited either complete survival or complete mortality of all seedlings and saplings. Therefore, the data were square root (X + 3/8) transformed (Zar 2010) before being analysed to stabilise the variance. A linear mixed model repeated measures analysis of variance (ANOVA) using PROC MIXED with the restricted maximum likelihood estimation method was used for analysis. Tukey's honestly significant difference (HSD) tests were then used to perform multiple comparisons between all pairs of treatments when ANOVA results indicated significant treatment effects.

6.5.5.2 Changes in cover percentages of botanical composition and logging debris

Data on the percentage cover (abundance) of sown grasses, volunteer grasses and weeds, debris and bare soil collected before the treatments and after 4-month intervals were analysed for each zone with a linear mixed model repeated measures analysis of variance (ANOVA) using PROC MIXED with the restricted maximum likelihood estimation method with the zone as the fixed effect, time of sampling as the repeated measure, and the quadrat and the quadrat nested in plot × zone treated as random effects. Assumption of normality of residuals was checked by PROC UNIVARIATE and since the preliminary results were not normally distributed, the cover percentage data were arsine square-root transformed before being analysed to stabilise the variance. Tukey's honestly significant difference (HSD) tests were then used to perform multiple comparisons between all pairs of treatments when ANOVA results indicated significant treatment effects.

6.5.5.3 Relationship between broom survival and cover percentage

To quantify the effects of botanical composition and debris on survival of broom seedlings and other stages over time (months) and space (plot) between zones, regression analyses were conducted with data from quadrats nested in each plot, zone, and assessment time (month) using PROC REG using adjusted R^2 selection and Akaike's Information Criterion (AIC) used to select the best suitable model (smallest AIC value). Nine independent variables (date, zone, plot, % Yorkshire fog, % volunteer grasses/weeds, % gorse, % debris, % bare soil and % broom) and three dependent variables (survival from 2009 to 2010, survival in 2010 and combined survival) were used in the models. Data on percentage cover were arsine square-root transformed and data on seedlings and other stages (counts) square root (X + 3/8) transformed (Zar 2010) before being analysed to stabilise the variance. Models were run with and without the variable % broom to see the effects of density-dependence on broom survival. If there was a significant effect of zone, data on broom survival from each zone were also fitted using regression analyses with eight independent variables (listed above but omitting zone) as above.

6.5.5.4 Demographic models

Matrix population modelling (Caswell 2001; Morris & Doak 2002) using the package popbio 2.4 (Stubben & Milligan 2007) in R 3.0.1 (R Core Team 2013) was used to assess differences in population growth rates (λ). A stage-based matrix population model was used based on Parker (2000) with a modification of stages in which individuals were divided into five vegetative classes and one reproductive class (Table 6.2). The form of this model was $\mathbf{n}_{(t+1)} = \mathbf{A}.\mathbf{n}_{(t)}$, of which $\mathbf{n}_{(t)}$ is a vector of stage abundance at time t and $\mathbf{A}$ is a matrix where the a_{ij} values represent the contributions of each stage to all other stages. A matrix model was developed for each zone using broom data collected from quadrats from 2009 to 2010. A seed stage was included in the model as it is one of the important components affecting transition probabilities of the population. Seed bank survival (s_1; Fig. 6.1) was the most uncertain parameter in this modelling but data on seed viability from laboratory work (see Section 6.5.2) showed that broom had a high survival rate (0.99) so this value was used to calculate seed bank survival as (1-germination proportion)×survival. Perturbation analyses (elasticity and sensitivity) were calculated for each matrix model. Elasticity analysis estimates the effect of a proportional change in the vital rates on λ. Sensitivity analysis estimates the impact of an absolute change in vital rates on λ (de Kroon *et al.* 1986; Caswell 2001). For example, if a small change in seedling survival markedly affects population growth, then seedling survival might be a target for control efforts. By contrast, if a change in seedling survival has minimal effects on population growth then it indicates that seedling survival should not become a focus of control efforts.

6.6. Results

Data on the vigour of *Pinus radiata* plants before and after the treatments (three months) are shown in Tables 6.3 and 6.4. There was high variability in the vigour of pines planted in plots before the treatments (Table 6.3). Three months after the treatments, the survival rate of pine was slightly different among the treatments but perhaps not because of herbicide effects (Table 6.4) and no further deaths occurred after the replanting of 100 trees on 25 May 2010 (see Section 6.5.1).

Table 6.3. Mean (with standard error of the mean in brackets) initial heights, diameters at the base and general condition (score, with 0 = very healthy and 10 = very unhealthy) of *Pinus radiata* before the treatment on 8 September 2009.

Treatment	*Height (cm)*			*Diameter at the base (mm)*			*Condition*
	Mean (SE)	*Minimum*	*Maximum*	*Mean (SE)*	*Minimum*	*Maximum*	
1	23.6(0.4)	15	31	5.9(0.2)	3	10	2.1
2	24.3(0.5)	16	30	6.3(0.3)	2	12	2.6
3	24.2(0.6)	14	34	6.2(0.2)	4	10	2.5
4	26.6(0.5)	20	34	5.7(0.3)	3	10	2.6
5	23.3(0.8)	6	32	6.3(0.3)	3	10	2.3
Mean	*24.2(0.5)*	–	–	*6.0(0.3)*	–	–	*2.4*

Table 6.4. Mean (with standard error of the mean in brackets) heights, diameters at the base and survival of *Pinus radiata* three months after treatment on 2 March 2010.

Treatment	*Height (cm)*			*Diameter at the base (mm)*			*Survival (%)*
	Mean (SE)	*Minimum*	*Maximum*	*Mean (SE)*	*Minimum*	*Maximum*	
1	30.6(1.3)	24	35	7.9(0.3)	6	9	74
2	30.9(2.1)	25	35	7.8(0.4)	7	9	95
3	30.6(1.4)	27	33	7.7(0.1)	7	8	78
4	33.5(1.6)	29	36	6.8(0.5)	6	8	88
5	35.1(2.3)	30	41	7.6(0.3)	7	8	95
Mean	*32.1(1.7)*	–	–	*7.6(0.3)*	–	–	*86*

6.6.1 Seed bank, seedling and sapling emergence and survival

Before the treatments, the broom seed bank was highly variable among the plots at the site, ranging from 0 to 35,925 seed m^{-2} (mean seed density of 14,473 seed m^{-2}). Moreover, seedling and sapling densities were relatively high in all sampling quadrats, ranging from 0 to 713 and from 0 to 40 $quadrat^{-1}$ (0.25 m^2), respectively. There was no significant difference in seed bank ($F_{3,133}$ = 2.35, P = 0.0751) nor in seedling and sapling densities ($F_{3,133}$ = 0.28, P = 0.8390) among the four zones before the treatments (Table 6.5). After the treatments, there was a significant effect of zone, date and their interaction on seed bank, seedling emergence, mortality and survival of broom with the exception of death following seedling emergence in 2010 (Table 6.6). Two values of mortality and survival were used to assess seedlings and saplings that emerged in 2009 and died/survived in 2010 (i.e. 2009–2010) and those that emerged in 2010 and died/ survived in the same year (i.e. 2010–2010). The death of seedlings and saplings (mortality 2009–2010) appeared soon after the application of herbicides and at a high rate and was very apparent by March 2010 in the Zones A, B and C (Table 6.6) after which no further deaths occurred. At the same time, seedling emergence recorded in these zones increased nearly four-fold from March 2010 to December 2010 with a high survival rate (Table 6.5). For the Zone D with no herbicide application, seedling emergence in 2010 increased three-fold from March 2010 to December 2010 but at about half the number of the other zones. Seedling survival over time was relatively high for both seedlings that emerged in 2009 and 2010 by the end of experiment (Table 6.5). However, these figures only show how seedlings changed over time but do not give information on actual stage transitions. This will be analysed by the matrix population models in Section 6.6.4.

Table 6.5. Mean (with standard error of the mean in brackets) number of seeds in the seed bank, emergence, mortality and survival of broom in each quadrat (0.25 m^2) across each zone over the assessment period. Column means sharing the same letter are not significantly different at $P > 0.05$.

Zone	*Seed bank*	*Cumulative Emergence*	*Mortality (2009–2010)*	*Mortality (2010– 2010)*	*Survival (2009– 2010)*	*Survival (2010– 2010)*
Before the treatment (November 2009)						
A (all vegetation cleared)	3876(254)	187(21)	–	–	–	–
B (broom and grass cleared)	3740(337)	197(22)	–	–	–	–
C (broom cleared)	4801(398)	164(28)	–	–	–	–
D (no herbicides)	3375(197)	214(22)	–	–	–	–
After the treatment						
March 2010						
A	3865(253)	10(2)	187(21)	0.1(0.1)	0	10(2)
	cd	bc	c	a	a	bd
B	3732(336)	8(1)	194(22)	0	3(0.8)	8(1)
	ad	ad	ab	a	bc	ac
C	4793(396)	8(2)	163(28)	0.1(0.1)	1(0.4)	8(2)
	ab	ac	b	a	b	ad
D	3171(197)	4(1)	3(1)	0	210(22)	4(1)
	bd	cd	bc	a	ab	cd
July 2010						
A	3858(253)	17(3)	0	0.3(0.1)	0	17(3)
	cd	bd	a	a	a	bd
B	3723(336)	17(2)	0	0.2(0.1)	3(0.8)	16(2)
	ad	ac	a	a	bc	ac
C	4786(395)	15(4)	0	0.3(0.1)	1(0.4)	15(4)
	ab	ad	a	a	b	ad
D	3366(191)	8(2)	2(1)	0.1(0.1)	204(21)	8(2)
	bd	cd	a	a	ab	cd
December 2010						
A	3831(252)	44(6)	0	0.4(0.1)	0	44(6)
	cd	c	a	cd	a	c
B	3694(333)	46(7)	0	0.2(0.1)	3(0.8)	46(7)
	ad	ab	a	bd	bc	ab
C	4755(390)	46(14)	0	0.6(0.2)	1(0.4)	45(14)
	ab	b	a	ab	b	b
D	3362(191)	13(3)	1(1)	0.4(0.2)	203(22)	12(3)
	bd	bc	a	bd	ab	bc

Table 6.6. Results of repeated measure analysis of variance testing the effect of zone, date and their interaction on seed bank, emergence, mortality and survival of broom in each quadrat (0.25 m^2) after the treatments. Bold values indicate statistically significant effects at $P < 0.05$.

Effect	*Num DF*	*Den DF*	*F*	*P*
Seed bank				
Zone	3	140	2.71	**0.0474**
Date	2	280	115.40	**<0.0001**
Zone × Date	6	280	10.11	**<0.0001**
Cumulative emergence				
Zone	3	141	7.79	**<0.0001**
Date	2	277	174.80	**<0.0001**
Zone × Date	6	278	12.91	**<0.0001**
Mortality (2009–2010)				
Zone	3	108	65.14	**<0.0001**
Date	2	191	598.17	**<0.0001**
Zone × Date	6	213	88.29	**<0.0001**
Mortality (2010–2010)				
Zone	3	146	1.23	0.3000
Date	2	277	17.85	**<0.0001**
Zone × Date	6	281	0.79	0.5822
Mortality (Combined)				
Zone	3	108	63.58	**<0.0001**
Date	2	191	581.95	**<0.0001**
Zone × Date	6	214	88.06	**<0.0001**
Survival (2009–2010)				
Zone	3	74.7	140.36	**<0.0001**
Date	2	187	4.74	**0.0098**
Zone × Date	6	222	7.12	**<0.0001**
Survival (2010–2010)				
Zone	3	141	7.86	**<0.0001**
Date	2	277	170.14	**<0.0001**
Zone × Date	6	278	13.53	**<0.0001**
Survival (Combined)				
Zone	3	141	71.88	**<0.0001**
Date	2	279	153.62	**<0.0001**
Zone × Date	6	280	26.08	**<0.0001**

6.6.2 Changes in cover percentages of botanical composition and debris

The sampling quadrats measured on 5 November 2009 (one month before herbicide application) showed a very low rate of establishment of Yorkshire fog, lotus, volunteer grasses or other weeds (Fig 6.6A) with a dominance of pine debris (55.1 to 62.6%) and broom (30.8 to 36.6%). There was no significant difference among the four zones (Table 6.7). However, by the time of herbicide application on 9 December 2009 (Fig. 6.6B), there was a slight change in the composition of grasses and weeds with Yorkshire fog at a higher density perhaps as a result of high rainfall and temperature (Fig. 6.3). There was no evidence of sown lotus present on any of the quadrats. There was a significant effect of zone, time and their interaction on changes in cover percentages of botanical composition and debris over time with the exception of gorse (Tables 6.7 and 6.8). Some of the main species present in quadrats were cleavers (*Galium aparine* L.), Scotch thistle (*Cirsium vulgare*), nodding thistle (*Carduus nutans* L.), catsear (*Hypochaeris radicata* L.), subterranean clover (*Trifolium subterraneum*), narrow-leaved plantain (*Plantago lanceolata*), gorse (*Ulex europaeus* L.), bracken (*Pteridium esculentum* L.*)* and geranium species.

After the herbicide treatments were applied in December 2009, there was a significant change in Zone A (terbuthylazine/hexazinone with all vegetation killed) with the cover of Yorkshire fog reducing to less than 1% by December 2009 and the volunteer grasses/weeds and broom to less than 1% by July 2010, although there was a subsequent increase to nearly 5% and 10%, respectively of these species by December 2010. There was a significant reduction in debris cover from 79% (March 2010) to less than 1% (December 2010) (Table 6.7).

In Zone B (clopyralid/triclopyr/picloram with grasses killed with haloxyfop but not the other weeds) broom cover was reduced to less than 1.5% by July 2010 followed by an increase to nearly 15% by December 2010. This treatment did not successfully control grasses with an increase in Yorkshire fog cover (6.7% by March 2010 to 14.1% by December 2010) and volunteer grasses/weeds (7.2 by March 2010 to 19.2% by December 2010). Debris cover decreased from 57% (March 2010) to less than 1% (December 2010) (Table 6.7).

In Zone C (clopyralid/triclopyr/picloram with grasses kept intact) broom was successfully killed and there was an increase in cover of Yorkshire fog from 39.8% (March 2010) to 55.5% (December) and less than 9% of volunteer grasses/weeds. Debris cover reduced from 57% (March 2010) to less than 1% (December 2010) (Table 6.7).

In Zone D (no herbicide application) there was a strong increase in broom cover (5.2 to 44.6%) and a reduction in cover of Yorkshire fog cover (56 to 47%), of volunteer grasses/weeds (5 to less than 2%) and of debris from 12.3% (March 2010) to less than 1% (December 2010) (Table 6.7).

The growth (height) of Yorkshire fog and volunteer grasses/weeds in comparison with that of broom (Fig. 6.7) was relatively similar over time within Zone A with a low rate of establishment compared with that of other zones presumably as the result of herbicide effects. In Zone B, the establishment of Yorkshire fog and volunteer grasses was slow until July 2010 but then increased in the period to December 2010, perhaps as a result of a reduction in herbicide activity and from more grass seeds being shed on the site from nearby and then germinating through the high rainfall period of late autumn (Fig. 6.3). Yorkshire fog established faster than broom seedlings in Zone C and was on average almost three times taller than the broom in March and July 2010 and five times by December 2010. By contrast, broom height in Zone D was nearly two times that of Yorkshire fog in March and July 2010 but was then out-grown by Yorkshire fog by December 2010 when most of the Yorkshire fog started flowering.

Figure 6.6. Pictures showing (A) a sampling quadrat on 5 November 2009 and (B) a spot-spraying treatment on 9 December 2009.

Table 6.7. Mean (with standard error of the mean in brackets) cover percentage (abundance) of Yorkshire fog, volunteer grasses/weeds, gorse, logging debris, broom and bare soil in each quadrat (0.25 m^2) across each zone over assessment times. Column means sharing the same letter are not significantly different at $P > 0.05$.

Zone	*Yorkshire fog*	*Volunteer grasses/weeds*	*Gorse*	*Debris*	*Broom*	*Bare soil*
Before the treatment (November 2009)						
A (all vegetation cleared)	0	0	0	62.6(4.5) a	31.3(4.5) a	0
B (broom and grass cleared)	0	0	0	60.5(5.5) a	30.8(5.5) a	0
C (broom cleared)	0	0	0	57.9(7.8) a	31.3(7.8) a	0
D (no herbicides)	0	0	0	55.1(5.3) a	36.6(5.3) a	0
After the treatment						
March 2010						
A	0.6(0.6) b	0.2(0.1) b	0 a	79.1(4.2) a	0.8(0.1) a	19.2(4.1) b
B	6.7(2.3) a	7.2(2.3) b	0 bc	56.9(5.2) c	1.0(0.2) bc	28.2(5.6) a
C	39.8(7.8) a	7.2(4.0) ab	0 b	27.4(4.2) c	0.8(0.2) b	24.8(6.7) ab
D	56.1(5.3) ab	5.0(2.6) ab	3.1(1.8) ab	12.3(3.0) ac	5.2(5.7) ab	18.2(3.5) ab
July 2010						
A	0.6(0.6) b	0.2(0.1) b	0 a	0.3(3.9) b	1.0(0.2) a	17.4(3.8) b
B	8.0(2.8) a	13.2(4.4) a	0 bc	0.2(5.6) c	1.3(0.2) bc	24.4(5.3) a
C	50.6(7.5) ab	6.6(4.4) ab	0 b	0.3(5.3) bc	1.4(0.4) b	17.5(5.0) ab
D	57.1(5.0) ab	2.5(1.4) ab	3.3(1.9) ab	0.1(3.0) bc	9.0(1.2) ab	15.9(3.6) ab
December 2010						
A	0.2(0.2) b	4.9(1.5) c	0 a	0.4(4.1) a	9.8(1.6) a	23.2(3.9) ab
B	14.1(3.8) a	19.2(5.2) ab	0 a	0.2(4.8) b	14.6(2.3) bc	18.8(5.2) c
C	55.5(8.0) ab	8.7(4.0) ab	0 a	0.6(4.6) a	8.3(2.4) b	8.8(4.1) ac
D	47.1(3.3) ab	1.6(0.6) bc	0.2(0.2) a	0.4(1.1) abc	44.2(2.6) ab	3.9(1.6) bc

Table 6.8. Results of repeated measure analysis of variance testing the effect of zone, date and their interaction on changes in cover percentages of Yorkshire fog, volunteer grasses/weeds, gorse, logging debris, broom and bare soil in each quadrat (0.25 m^2) across each zone and assessment times. Bold values indicate statistically significant effects at $P < 0.05$.

Effect	*Num DF*	*Den DF*	*F*	*P*
Yorkshire fog				
Zone	3	83	71.36	**<0.0001**
Date	3	442	138.06	**<0.0001**
Zone × Date	9	453	42.04	**<0.0001**
Volunteer grasses/weeds				
Zone	3	175	8.79	**<0.0001**
Date	3	426	22.56	**<0.0001**
Zone × Date	9	440	4.32	**<0.0001**
Gorse				
Zone	3	232	2.63	**0.0507**
Date	3	463	1.53	0.2054
Zone × Date	9	475	2.21	**0.0202**
Debris				
Zone	3	153	51.74	**<0.0001**
Date	3	415	42.68	**<0.0001**
Zone × Date	9	423	26.12	**<0.0001**
Broom				
Zone	3	105	23.62	**<0.0001**
Date	3	257	177.84	**<.00001**
Zone × Date	9	308	5.84	**<0.0001**
Bare soil				
Zone	3	190	2.69	**0.0476**
Date	3	440	100.61	**<0.0001**
Zone × Date	9	450	5.04	**<0.0001**

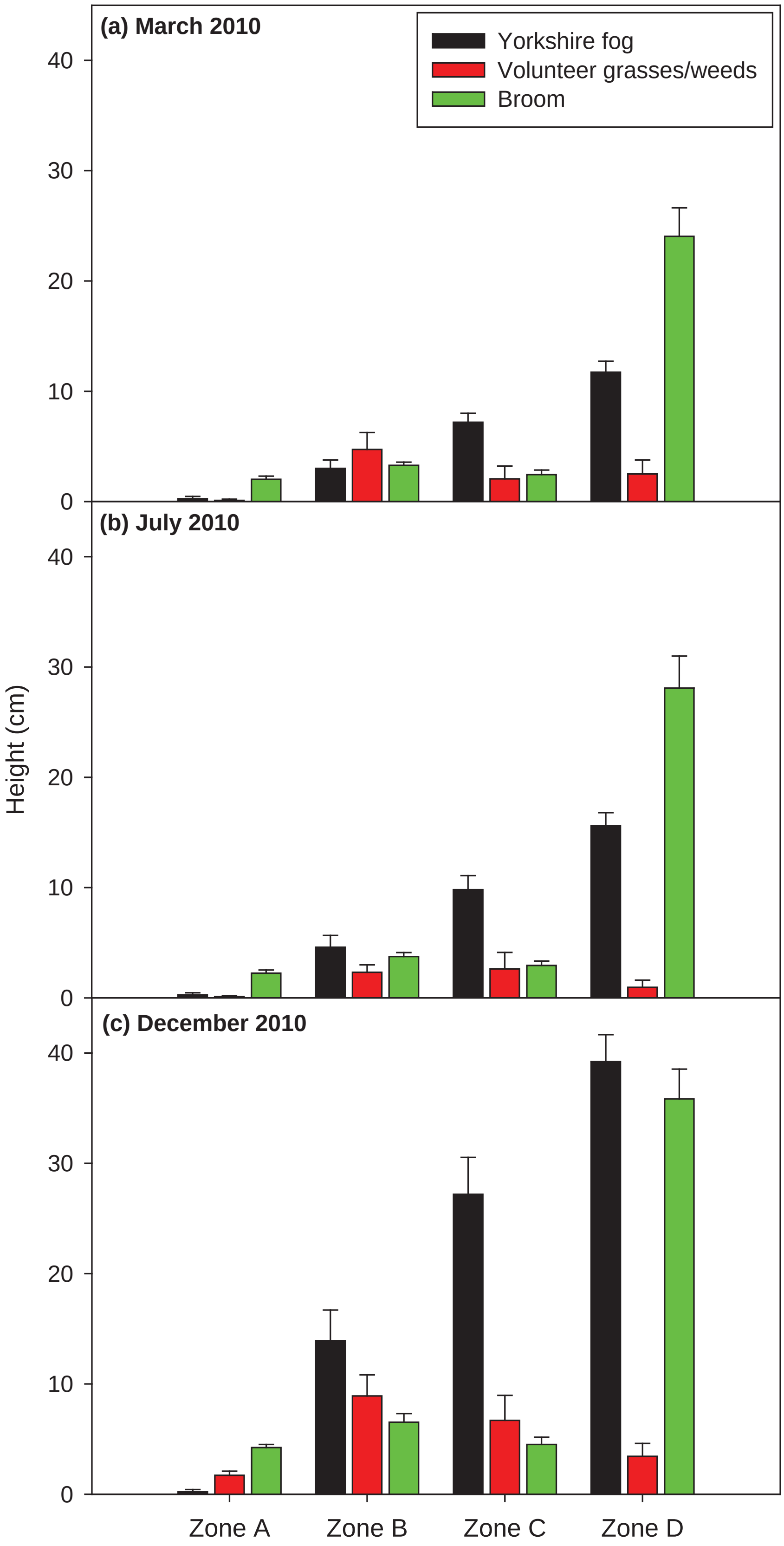


Figure 6.7. Mean height (with one standard error of the mean) of Yorkshire fog, volunteer grasses/weeds and broom across four zones after the treatment.

6.6.3 Relationship between broom survival and cover percentage

Results of the regression analyses testing the effects of ground cover percentage on broom survival are shown in Table 6.9. Broom survival was highly dependent on changes in proportion of cover percentages over time and space but the magnitude was different among zones. There were significant differences in survival of broom that emerged before and after the treatments presumably because of changes in the cover of vegetation and logging debris. Adding or removing the variable broom cover percentage affected the model's fit in Zones A and C but not for the others.

Table 6.9. Results of regression analyses quantifying the changes in broom survival (2009–2010 and 2010–2010) with respect to cover percentage variables over time across the four zones (see the text for details).

Broom survival	Number of variables	R^2	AIC	SSE	[1]Variables in model
Broom cover included					
2009–2010	8	0.71	1121.00	5550.68	D Z P Y V De Br Bs
2010–2010	9	0.47	603.96	1638.35	D Z Y V G De Br Bs
Combined	7	0.59	1159.05	6089.88	Z P V G De Br Bs
Broom cover excluded					
2009–2010	7	0.71	1121.24	5579.45	D Z P Y V De Bs
2009–2010	5	0.31	701.48	2131.22	D Z P Y De
Combined	7	0.56	1194.88	6616.48	D Z P Y V De Bs
Zone A (Broom cover included)					
2009–2010	3	0.04	-724.93	0.87	De Br Bs
2010–2010	3	0.79	88.23	251.39	P Y Br
Combined	3	0.79	87.84	250.70	P Y Br
Zone A (Broom cover excluded)					
2009–2010	2	0.03	-725.63	0.89	De Bs
2010–2010	6	0.61	183.51	467.32	D P Y V De Bs
Combined	6	0.61	183.01	465.97	D P Y V De Bs
Zone B (Broom cover included)					
2009–2010	4	0.22	-13.34	75.28	D P De Br
2010–2010	4	0.56	100.36	246.05	D Y Br Bs
Combined	3	0.59	91.82	229.87	D De Br
Zone B (Broom cover excluded)					
2009–2010	2	0.12	-6.41	84.35	P De

Broom survival	Number of variables	R^2	AIC	SSE	[1]Variables in model
2010–2010	5	0.47	122.00	301.95	D Y V De Bs
Combined	5	0.46	122.19	302.52	D Y V De Bs
Zone C(Broom cover included)					
2009–2010	6	0.51	-69.66	8.40	D P Y V De Bs
2010–2010	3	0.85	23.73	66.62	P De Br
Combined	3	0.85	23.37	66.12	P De Br
Zone C(Broom cover excluded)					
2009–2010	6	0.51	-69.66	8.40	D P Y V De Bs
2010–2010	6	0.43	94.97	259.33	D P Y V De Bs
Combined	6	0.45	93.25	250.21	D P Y V De Bs
Zone D (Broom cover included)					
2009–2010	6	0.39	426.08	2518.70	D P V G Br Bs
2010–2010	5	0.37	135.66	339.88	D P De Br Bs
Combined	6	0.38	427.63	2545.90	D P V G Br Bs
Zone D (Broom cover excluded)					
2009–2010	5	0.36	430.76	2638.28	P Y V De Bs
2010–2010	5	0.36	141.64	349.39	D P Y V G Bs
Combined	5	0.35	431.69	2655.36	P Y V De Bs

[1]Note: D (Date), Z (Zone), P (Plot), Y(Yorkshire fog), V (Volunteer grasses/weeds), G (Gorse), De (Logging debris), Br (Broom) and Bs (Bare soil).

6.6.4 Matrix models for broom under various zones

In this study, 27,173 seedlings and 954 saplings were mapped and their fates followed from before the herbicide application. An additional number of new seedlings that survived and subsequently moved to other stages were shown in four matrix models developed for the four zones. Surprisingly, all population models for the four zones showed decreasing broom populations (λ <1).

The matrix model for Zone A (terbuthylazine/hexazinone with all vegetation killed) (Fig. 6.8) showed that a very high proportion of seeds (97.86%) remained in the soil while 0.45% became seedlings and 0.69% saplings. The proportion of seedlings emerging from 2009 that subsequently died in 2010 as the result of the treatment was very high (100%) with an additional small number of seedling deaths from those that emerged in 2010. The proportion of saplings that emerged from 2009 and then died in 2010 as the result of the treatment was also high (99.67%) with the remaining surviving by the end of the experiment.

The matrix model for Zone B (clopyralid/triclopyr/picloram with grasses killed with haloxyfop but not the other weeds) (Fig. 6.9) indicated a similar pattern to that shown in Zone A with a high proportion of deaths of broom seedlings (99%) and saplings (87.4%) from 2009 as a result of the treatment and again with a high proportion of seeds left in the soil (97.78%). Less than 1% of seeds became seedlings and saplings, respectively and a similar proportion changed from seedlings to saplings while more than 1% remained as saplings in 2010. Interestingly, there was a direct transition from seeds to small juveniles and from seeds to medium juveniles although at a very low rate. Similarly, seedlings could change to small juveniles and to medium juveniles as well as saplings did although these transitions were both very rare.

The matrix model for Zone C (clopyralid/triclopyr/picloram with grasses kept intact) (Fig. 6.10) followed a similar pattern to Zone B with a low proportion of transitions of seeds to seedlings and of seedlings to saplings as well as a high proportion of deaths of seedlings (99.76%) and saplings (88.64%) and 97.78% of seeds still in the soil. There was a direct transition from seeds to medium juveniles although at a very low rate. A small proportion of seedlings (less than 0.3%) moved to adults. The proportion of saplings which remained at that stage was high (11%) and about 5.7% of saplings moved to adults in 2010.

The most complete matrix model was for Zone D (no herbicide application) (Fig. 6.11). There were a low proportion of deaths of seedlings (5%) in 2010 again with a high proportion of seeds remaining in the soil (98.55%). Seeds, seedlings, and saplings all frequently remained in stasis or advanced to other stages and there was no regression. Sapling stasis was frequent (30.1%) and there was frequent recruitment to this stage from seedlings (93%). Moreover, 30% of saplings became large juveniles with a concomitant likelihood of flowering and setting seeds. Therefore, the most significant transitions were from seedlings to saplings and from saplings to large juveniles. The high proportion of sapling mortality (29%) might be due to density-dependence effects and grazing by herbivores (probably hares). Of the 478 plants tagged on quadrats in this zone, 89 (19%) were grazed and 30 (6.3%) started flowering (20 from large juveniles (67%) and 10 from adults (33%)) by the end of the experiment.

Results from the sensitivity analyses (Figs 6.12 and 6.13) further confirmed the result from matrix models in which a cohort of the population could advance from seeds to saplings in Zone A within one year. Both Zones B and C followed a similar pattern in which the population could advance from seeds to medium juveniles although the highest likelihood of transition was from seeds to seedlings and seeds to saplings but there was a probability of changing from seedlings to adults and saplings to adults in Zone C. The worst scenario was seen for Zone D with no herbicides in which the population is predicted to frequently advance to adults with medium juveniles as an intermediate stage (Fig. 6.12). There was no difference in results of elasticity analyses in which seeds remained at a stable stage (Fig. 6.13) and that it was the key element that could affect the changes in vital rates in this broom population.

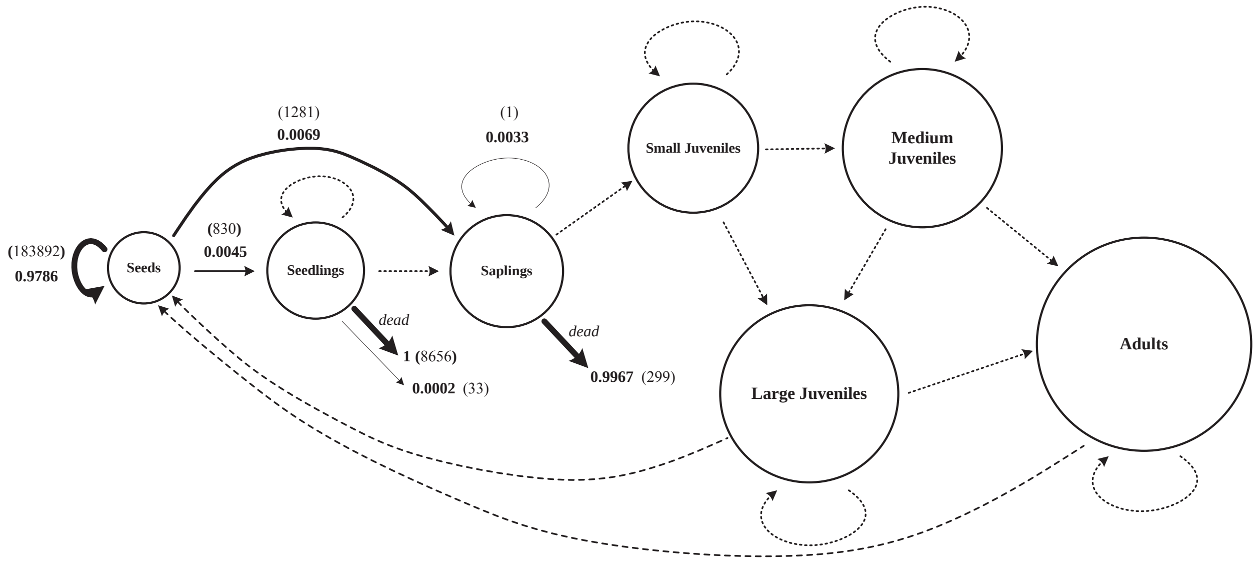


Figure 6.8. Matrix population model for Zone A (terbuthylazine/hexazinone with all vegetation killed). Bold values show probabilities of transition between stages or remaining at the same stage (values in brackets are the real number in that stage).

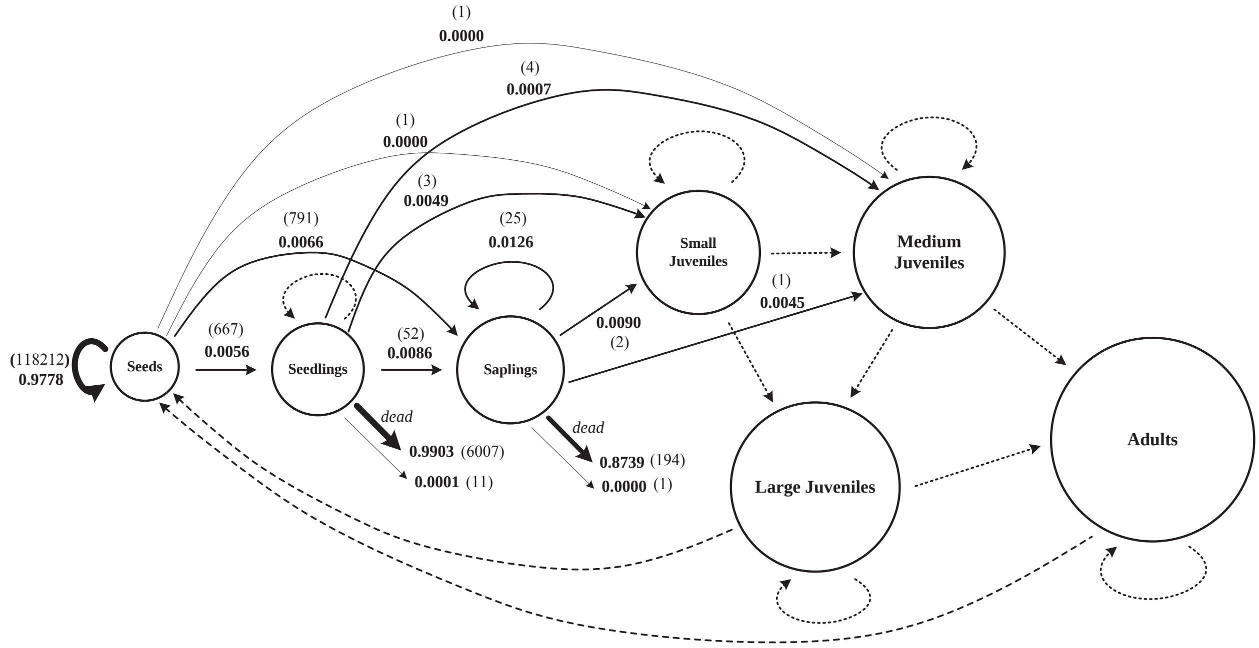


Figure 6.9. Matrix population model for Zone B (clopyralid/triclopyr/picloram with grasses killed by haloxyfop but not all other weeds). Bold values show probabilities of transition between stages or remaining at the same stage (values in brackets are the real number in that stage).

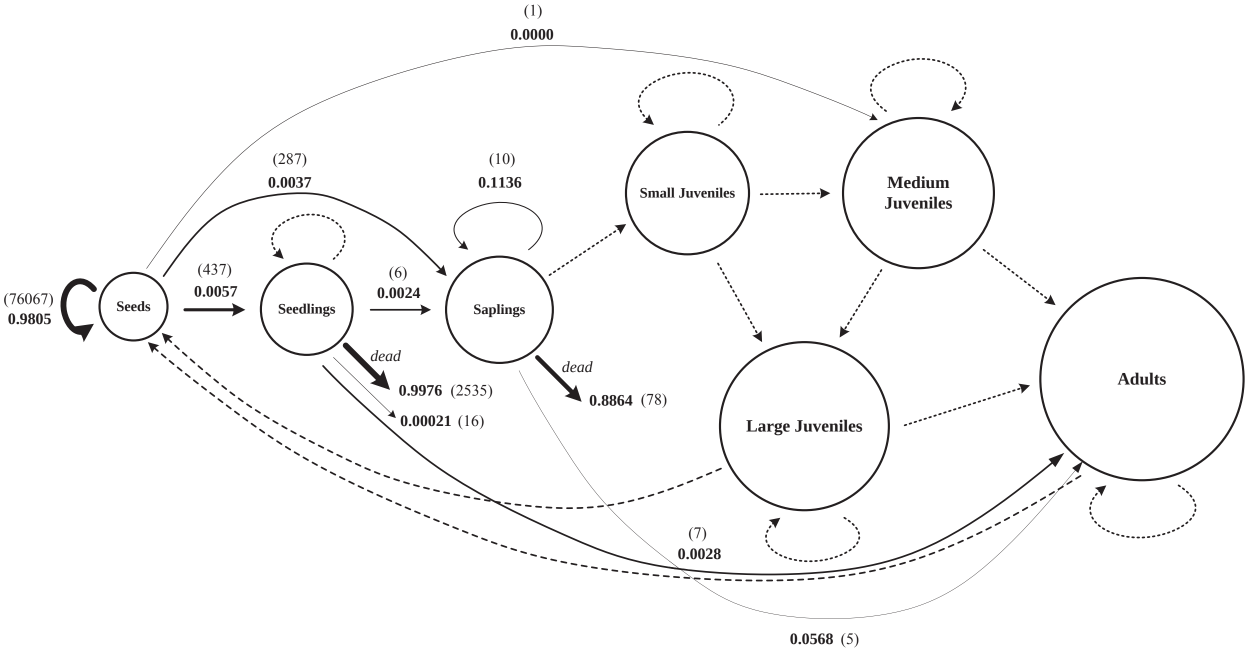


Figure 6.10. Matrix population model for Zone C (clopyralid/triclopyr/picloram with grasses kept intact). Bold values show probabilities of transition between stages or remaining at the same stage (values in brackets are the real number in that stage).

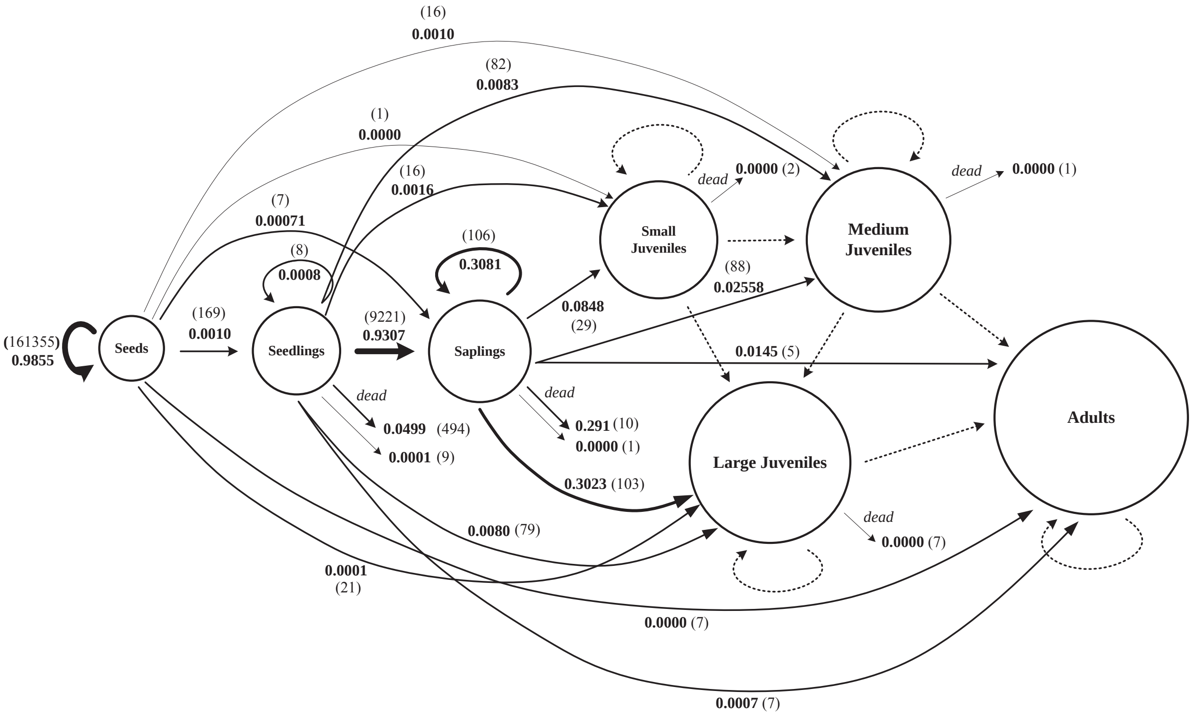
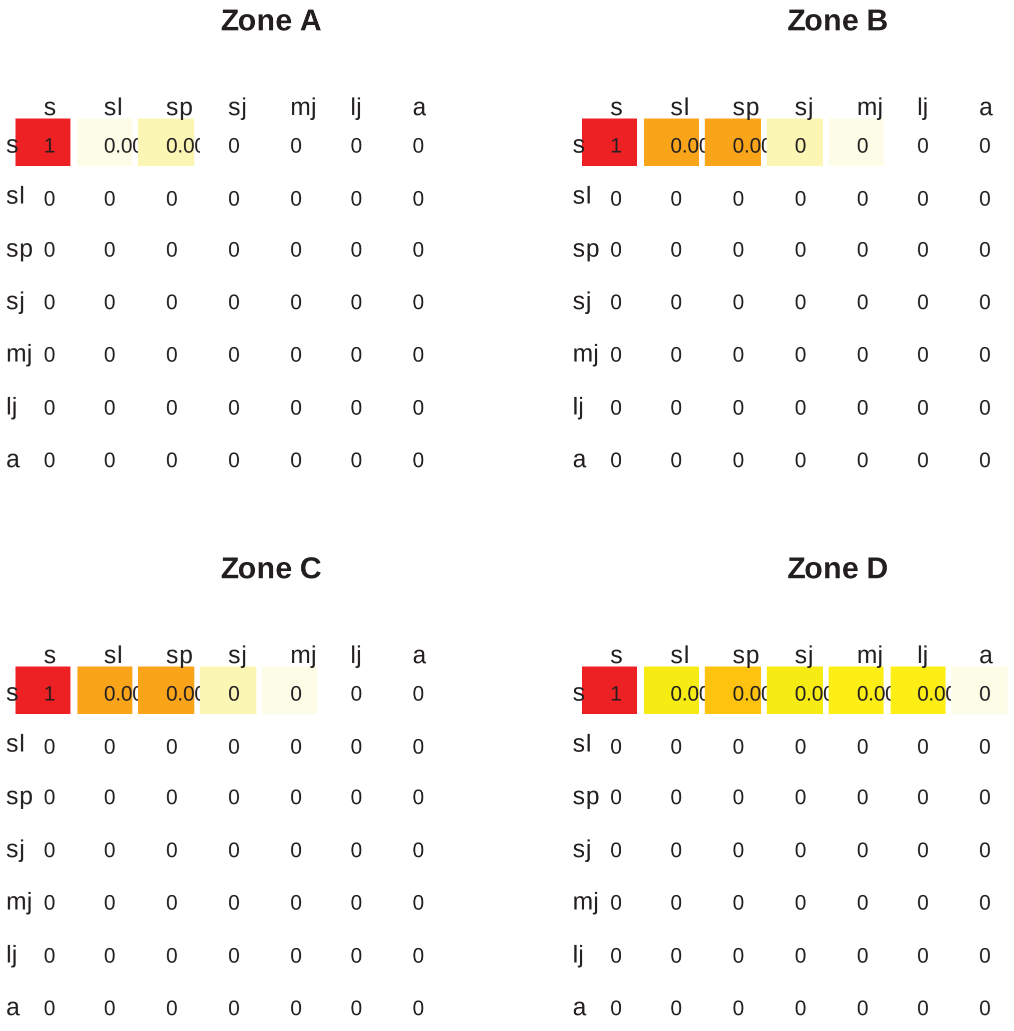


Figure 6.11. Matrix population model for Zone D (no herbicide application). Bold values show probabilities of transition between stages or remaining at the same stage (values in brackets are the real number in that stage).



Zone A

	s	sl	sp	sj	mj	lj	a
s	1	0.0	0.0	0	0	0	0
sl	0	0	0	0	0	0	0
sp	0	0	0	0	0	0	0
sj	0	0	0	0	0	0	0
mj	0	0	0	0	0	0	0
lj	0	0	0	0	0	0	0
a	0	0	0	0	0	0	0

Zone B

	s	sl	sp	sj	mj	lj	a
s	1	0.0	0.0	0	0	0	0
sl	0	0	0	0	0	0	0
sp	0	0	0	0	0	0	0
sj	0	0	0	0	0	0	0
mj	0	0	0	0	0	0	0
lj	0	0	0	0	0	0	0
a	0	0	0	0	0	0	0

Zone C

	s	sl	sp	sj	mj	lj	a
s	1	0.0	0.0	0	0	0	0
sl	0	0	0	0	0	0	0
sp	0	0	0	0	0	0	0
sj	0	0	0	0	0	0	0
mj	0	0	0	0	0	0	0
lj	0	0	0	0	0	0	0
a	0	0	0	0	0	0	0

Zone D

	s	sl	sp	sj	mj	lj	a
s	1	0.0	0.0	0.0	0.0	0.0	0
sl	0	0	0	0	0	0	0
sp	0	0	0	0	0	0	0
sj	0	0	0	0	0	0	0
mj	0	0	0	0	0	0	0
lj	0	0	0	0	0	0	0
a	0	0	0	0	0	0	0

Figure 6.12. Sensitivity matrix for estimating the impact of an absolute change in vital rates on population growth rate (λ) in each zone. Transition stages: s (seed), sl (seedling), sp (sapling), sj (small juvenile), (mj) medium juvenile, lj (large juvenile) and a (adult).

Zone A

	s	sl	sp	sj	mj	lj	a
s	1	0	0	0	0	0	0
sl	0	0	0	0	0	0	0
sp	0	0	0	0	0	0	0
sj	0	0	0	0	0	0	0
mj	0	0	0	0	0	0	0
lj	0	0	0	0	0	0	0
a	0	0	0	0	0	0	0

Zone B

	s	sl	sp	sj	mj	lj	a
s	1	0	0	0	0	0	0
sl	0	0	0	0	0	0	0
sp	0	0	0	0	0	0	0
sj	0	0	0	0	0	0	0
mj	0	0	0	0	0	0	0
lj	0	0	0	0	0	0	0
a	0	0	0	0	0	0	0

Zone C

	s	sl	sp	sj	mj	lj	a
s	1	0	0	0	0	0	0
sl	0	0	0	0	0	0	0
sp	0	0	0	0	0	0	0
sj	0	0	0	0	0	0	0
mj	0	0	0	0	0	0	0
lj	0	0	0	0	0	0	0
a	0	0	0	0	0	0	0

Zone D

	s	sl	sp	sj	mj	lj	a
s	1	0	0	0	0	0	0
sl	0	0	0	0	0	0	0
sp	0	0	0	0	0	0	0
sj	0	0	0	0	0	0	0
mj	0	0	0	0	0	0	0
lj	0	0	0	0	0	0	0
a	0	0	0	0	0	0	0

Figure 6.13. Elasticity matrix for estimating the effect of a proportional change in the vital rates on population growth rates (λ*)* in each zone. Transition stages: s (seed), sl (seedling), sp (sapling), sj (small juvenile), (mj) medium juvenile, lj (large juvenile) and a (adult)

6.7 Discussion

After initial site disturbance such as harvesting and site preparation, an alternative strategy to direct weed removal using herbicides is trying to exclude unwanted species by over-sowing the site with a more desirable cover species. However, to be viable, the over-sowing species must either have minimum impacts on crop growth or, more realistically, must be easier to control than the species to be excluded. In practice, spot control using herbicides to release crop trees from competition with over-sown species is widely used (Richardson 1993). In this study, an integrated approach was tested using knockdown and residual herbicides to control broom with and without grass control during the first year of stand establishment. The different herbicide combinations applied did generate significant variability in the dynamics of this broom population.

Among the four herbicide treatments applied, three assessment zones were used for comparing how effective these treatments were on controlling broom seedlings. The most effective treatment was the application of a terbuthylazine (8500 g a.i. ha^{-1}) + hexazinone (1500 g a.i. ha^{-1}) mix (Zone A) that totally killed old broom seedlings and saplings present in the quadrats in 2009. The application of a clopyralid (8500 g a.i.ha^{-1}) + triclopyr (1500 g a.i. ha^{-1}) + picloram (8500 g a.i. ha^{-1}) mix to control broom along with haloxyfop (8500 g a.i. ha^{-1}) to control grasses (Zone B) and without the haloxyfop (Zone C) also gave as good control of old broom seedlings and saplings as Zone A. The findings obtained from this trial confirmed the results in Chapter 4 in which both the terbuthylazine (8500 g a.i. ha^{-1}) + hexazinone (1500 g a.i. ha^{-1}) mix and triclopyr (3000 g a.i. ha^{-1}) + picloram (1000 g a.i. ha^{-1}) mix showed high persistence in controlling broom seedlings.

Although the generally low rate of broom seedling emergence that was relatively similar among these zones was perhaps mainly due to the residual effects of herbicides, another reason preventing broom seeds from germination could be the high cover of logging debris present in quadrats before the application of herbicides and at least six months after the treatments (July 2010). Harrington and Schoenholtz (2010) applied three logging debris treatments (dispersed, piled and removed) along with an application of triclopyr (2800 g a.i. ha^{-1}) with surfactant and found that two to three years after the treatment, the cover of broom was more than 20% greater where logging debris was piled than where it was dispersed. In my study, across the herbicide treatments, there was a relatively similar rate of seedling emergence and a very high rate of survival perhaps due to residual effects of the various herbicides dissipating and less competition from grasses. This was clearly shown in Zone C where clopyralid/triclopyr/picloram had been applied but the grasses left intact and Zone D where no herbicide applications were used which resulted in a high rate of survival of broom seedlings and a high probability of transitions to other stages.

There was a very low rate of establishment of Yorkshire fog (sown at 7 kg ha^{-1}) and no establishment of lotus (sown at 2 kg ha^{-1}) at the site. Note that the rate of Yorkshire fog sown in this trial was nearly double the rate I used in the Chapter 3 (4 kg ha^{-1}). These grasses had been sown early in May 2009, which was nearly two months after the site was aerially desiccated with glyphosate and metsulfuron-methyl at the end of February 2009. Harrington and He (2010) indicated that Yorkshire fog has an intermediate tolerance and lotus was sensitive to metsulfuron-methyl such that they required at least three months delay to be safely sown in spring. Another reason might be the abundance of logging debris created during windrowing that might have prevented the grass seeds from germinating and the same may be true of broom. For whatever reason, the grasses established poorly at this site, reducing the level of competition expected when designing the trial.

The demographic approach used in my study to analyse the effects of herbicide application and ground covers differs from prospective approaches such as sensitivity and elasticity analysis that evaluate management strategies before they are implemented (Heppell *et al.* 2000; Menges 2000; Morris & Doak 2002). Most often, these approaches combine demographic models for unmanaged populations (i.e. Zone D in my study) with qualitative estimates of the direction in which vital rates are likely to be affected by management (Crone *et al.* 2009). Among matrix models developed for broom and discussed in Chapter 1, no model actually tested how the broom population change was predicted to occur because of a direct management strategy. In this study, sensitivities and elasticities were used to determine which life stages (e.g., juveniles vs. adults) or demographic rates (e.g., survival vs. reproduction) should be the primary targets of management efforts aimed at the restriction of broom population size.

The planting site in this study was relatively ideal for testing management strategies and seeing how broom population proceeded through changes in their vital rates, although the competition from sown grasses and the other weeds was not as high as expected. For species inhabiting ecosystems dominated by disturbances, such as fires or hurricanes, temporal variation in vital rates (survival, growth and reproduction) will usually have two components: between-phase and within-phase variability (Morris *et al.* 2006). First, vital rates will vary as a function of the phase in the cycle of disturbance and recovery (e.g. 0, 1, 2, etc. years post-fire). For example, seed germination may be higher on average in years immediately following fires than it is in years long after the last fire occurred. This type of variation is called between-phase variability. Second, even among years that represent equivalent disturbance phases, vital rates will vary due to fluctuating environmental factors that are unrelated, or only weakly related, to the disturbance phase within-phase variability (Morris *et al.* 2006).

The four models developed here reflected the realised fates of the broom populations at the site during the 12 months after the application of treatments. The most simple and effective treatment occurred within Zone A (terbuthylazine/hexazinone with all vegetation killed) in which the broom population remained largely suppressed at the seedling and sapling stages for the first 12 months after treatment. The matrix model for Zone B (clopyralid/triclopyr/picloram with grasses killed but not other weeds) also indicated successful control of broom seedlings but showed a potential reinvasion threat from the seed bank with a small likelihood of transition from seeds to small juveniles and from seeds to medium juveniles within the 12 months after treatment.

In many ways, herbicide management is analogous to the impacts of natural disturbances such as hurricanes, fires, and floods. These disturbances have negative short-term impacts but typically improve conditions for surviving or recolonising plants. In the same way, the net effect of herbicide use is only positive if the short-term negative effects are followed by a period when herbicide is no longer persistent in the soil, but competition by weeds and other native species is enhanced (Crone *et al.* 2009). The probability of changing from seedlings to large juveniles and adults in Zone C (clopyralid/triclopyr/picloram with grasses kept intact) indicated that the effects of herbicides were starting to dissipate by the end of the trial and if no further control measures were taken the broom population is likely to converge with that of Zone D (no herbicides). Although there was a low probability of transition from seeds to seedlings and from seeds to saplings in Zone D, a high survival rate of saplings and a high transition from seedlings to saplings will keep this population remaining at a steady state over time. This recruitment resulted in a high density of medium-sized juveniles and adults that started flowering and setting seeds by the end of the experiment.

Compared with other countries within the native and exotic range of broom, the broom populations in New Zealand appear to have a relatively high probability of seedling establishment (Paynter *et al.* 1996). However and significantly, there appears to be a high degree of variability in the probability of seedling survival in both native and exotic ranges and the results obtained from my study have been added for comparison (Table 6.10).

Several limitations could affect outcomes of matrix models in my study. First, the data obtained here were just collected for one year after the application of treatments and that might be not enough to make models useful beyond that first year. Second, the data were only collected three times within the year and therefore might have missed some of the new seedlings. Third, the grass establishment was poor so it is hard to capture what would happen at sites where grass covers established properly. Finally, the study was based on only one site for testing the effects of management and building the models so it might not accurately predict the outcome in other *P. radiata* stands. These restrictions however are evident for other demographic studies.

Table 6.10. Probability of a seed becoming a seedling and the probability of survival to first flowering in the UK, France, Australia, New Zealand and USA. Note that references were listed in order of research publication date and ends with this study (in bold).

Country	*Probability of a seed becoming a seedling*	*Probability of a seedling survival to reproduction*	*§Reference*
Native habitats			
UK	0.036	0.58	2
France	0.013	0.16	2
France	0 (undisturbed plots)	0.39	3
	0.14 (disturbed plots)	–	
France	0.445	0.848	9
France	0.445	0.800	11
Exotic habitats			
Australia	0.006–0.04 in autumn	–	1
	0–0.002 in spring	–	
Australia	0.02	0.06	3
Australia	0.33	0.02	6
Australia	0.023	0.005–0.05 (disturbed plots)	7
		0.006 (control plots)	
USA	–	0.05	5
New Zealand	0–0.47	–	4
New Zealand	–	0.46	2
New Zealand	0.47	–	8
New Zealand		–	10
New Zealand	**0.0057**	**0.0028 (Zone C)**	**12**
	0.0001	**0.0007 (Zone D)**	

§Reference: [1]Hosking *et al.* (1996); [2]Paynter *et al.* (1996); [3]Paynter *et al.* (1998); [4]Williams (1981); [5]Bossard and Rejmánek (1994); [6]Downey and Smith (2000); [7]Sheppard *et al.* (2002); [8]Bellingham and Coomes (2003); [9]Magda *et al.* (2009); [10]Paynter *et al.* (2010); [11]da Silveira Pontes *et al.* (2012); [12]this study (see Figs.6.9 and 6.10).

6.8 Implications for forest managements and future research

Among the different strategies used in this study, the application of herbicides appeared to result in the short-term control of broom initially but their residual activity soon dissipated. Alternatively, if the site is covered with logging debris, it might be useful to keep that cover intact as a broom suppressant but care must be taken as this might restrict the successful establishment of over-sown grasses and herbicide effects. In this study, low rate of establishment of grasses at this site indicated that the forestry management was not good as establishing grasses with sufficient density to compete with large-seeded weeds like gorse and broom. Getting high density of grasses however is not easy due to the high variability of environmental conditions at forest sites and future research is needed to deal with this problem.

CHAPTER 7
SYNTHESIS

7.1 Introduction

Charles Elton, a pioneer in population ecology, wrote on how ecological explosions were threatening the world (Elton 1958). Nearly half a century later, his early warning has become one of the most important environmental crises of our time (Jose *et al.* 2009) which has become a fascinating research topic—invasion ecology. Biological invasions have caused more species extinctions than human-induced climate change (D'Antonio & Vitousek 1992), and are the second leading cause of species extinctions after habitat loss (Wilcove *et al.* 1998; Jose *et al.* 2009). Biological invasion is one of the major reasons of biodiversity depletion (Jose *et al.* 2009).

The widespread recognition that non-native plants can have significant biological and economic effects on the habitats they invade has led to a variety of strategies to remove them (Corbin & D'Antonio 2012). In New Zealand, the 'overwhelming ...competing power of exotics' is strongly context dependent and some aspects of vegetation seem less unusual with increased knowledge, but others remain 'problems' (Wilson & Lee 2012).

This project worked with broom (*Cytisus scoparius*), a species that has been recognised as a major weed in eight regions of the world (Rejmánek & Richardson 2013) and become a weed of forestry in New Zealand. This project started with exploring some aspects of broom ecology (i.e. seed bank, seed germination, and seedling ecology) as drivers for finding and testing management options (ground covers and herbicides and the integrated use of these).

7.2 Thesis findings

The seed bank plays an important part in the life cycle of broom as germination from seeds is the most effective way for reproduction beside its capability to resprout from stumps and root fragments. Once the broom plant matures, it can build up a large number of seeds underground stored in seed banks that persist for a long time (Chapters

2 and 6). I assessed the variability in the size of the broom seed bank in different *Pinus radiata* stands (Section 2.3.1). Seeds were found at a variety of depths but mostly at 0–10 cm (Chapter 2) with a density reaching 36,000 seeds m^{-2} (Chapter 6). A seed's position in the soil profile probably influences its likelihood of germination. My results agree with other studies in New Zealand, where broom seed was generally found in the top 5–6 cm of soil and occasionally as deep as 15 cm (Williams 1981; Partridge 1989). In my study, the middle-aged (9 years) and oldest stands of pine trees (30 years) both showed large broom seed banks (Chapter 2). Surprisingly, after 30 years under pines, the seeds remained at a high density, presumably due to new seeds being produced throughout the 30 years since it was planted, especially during the first 10 years when the trees were less competitive and broom plants tall and dense, but also due to the long-lived nature of the seeds. Having a disturbed site does not increase seed numbers directly. Information from Chapter 6 suggests that only a small proportion of the seed bank gets exhausted through disturbance of the site. The high density of broom seeds in soil seed banks is the key reason for invasion and persistence of this species in forest sites.

The high dormancy and longevity of broom seeds is a very important factor for finding suitable options of controlling this species. Under laboratory conditions, seeds showed a high viability (Sections 2.3.1 and 2.3.2) with a rapid germination rate once scarified. These results suggest that broom may remain dormant due to an impervious seed coat. Seeds can germinate at different depths to 2 cm but depends on whether or not the seeds are scarified (Section 2.3.2), suggesting that germination success under field conditions depends on factors other than just than seed dormancy. Unscarified seeds exposed to bare soil (simulating disturbance) would have been subject to changing cold/hot temperatures, which presumably caused seed coats to break over time. Scarified seeds soon germinated but many of these seedlings then died, presumably due to changes in soil moisture in summer at the site or another factor affecting seed death might have been fungal activity because the seed coat was broken.

Seedling emergence is not affected by disturbance (with or without ground covers) or herbivory (caged or uncaged). Rabbits are partly responsible for the mortality of seedlings (Section 2.3.3). Broom seedling survival may have also been affected by the

changing seasons and soil conditions, as many young seedlings appeared to die when the soil became dry especially in the disturbed plots.
The results from these early experiments suggested that leaving sites cleared if they have a persistent broom seed bank might not be wise since temperature fluctuations will gradually break the seed coat and once seedling emergence takes place, rapid growth can occur. Most of the rest of the project therefore dealt with the ways of controlling broom germinating from seed banks.

A simple, environmentally-friendly and economical control measure is over-sowing sites with ground covers several months after the sites have been prepared in a hope that they will soon establish and suppress broom germinating from the soil seed bank (Chapter 3). Up to now, there has been no published work on assessing how successful these ground covers are for controlling broom seedlings. By sowing broom seeds and seeds of different ground cover species (Yorkshire fog, Italian ryegrass, and perennial ryegrass) at different rates and seasons, I have shown that the competitive effect from these species on broom seedlings might be successful only when the over-sowing of grasses has occurred some months before the broom germinated. The grasses needed to be well established prior to germination of the broom. Growth of broom however might be affected under dense swards of Yorkshire fog. Over-sowing of grasses in autumn seems to be a suitable option to get better control of broom. This result however might not easily be obtained when the seeds are sown in forest sites, which tend to be highly variable in topographic and growing conditions. The grass swards in Chapter 3 would have been more competitive than the swards at Section 2.3.3 as they had established quite recently and were still at high densities. Therefore, ground covers will not be suitable for seedling broom control when both establish at the same time.

Use of ground covers therefore must be combined with the application of herbicides that kill broom seedlings during the early stages of pine establishment (Chapter 5), provided they do not adversely affect the grass sward. Once the sward has established, the grass should then stop further broom from establishing. In this study, I have shown that if broom and grasses are establishing at similar times at the start of a new rotation of *P. radiata*, the broom needs to be controlled either by an application of clopyralid or triclopyr, which will kill the broom but not the grasses. In addition, these herbicides need to have residual soil activity to further control seedlings as they germinate (Chapter 4). Most herbicides routinely used in forestry have residues that will have some effects on broom germinating from soil seed bank. Seedlings can be killed or their growth restricted depending on the rates applied. Although less persistent than other herbicides, metsulfuron-methyl is normally used during replanting to kill broom and weeds before sowing grasses and planting pine trees. Hexazinone and the terbuthylazine/hexazinone mixture will kill broom and grasses after the pine has been planted.

If broom has already established within the young pines, they need to be removed using selective herbicides that kill broom plants but not the pines (Chapter 5). There is little published information on how effective these herbicides are on broom and their safety to young pines. The results from my trial indicate that broom can be selectively removed from *P. radiata* during the first nine months of growth using herbicide mixtures based on clopyralid and triclopyr, clopyralid and picloram, or terbuthylazine. Among the herbicides tested, fluroxypyr would not be recommended to use with pine due to its phytotoxicity. All of the other herbicides tested are registered for used in *P. radiata* to control broom and other weeds but their effectiveness and safety to *P. radiata* had not clearly described in published work on broom control.

My research, therefore, showed that two types of herbicide options are available for controlling broom: (1) herbicides (i.e. clopyralid + triclopyr and clopyralid + picloram mixes) that kill broom while leaving grass ground cover intact so that the grasses can suppress further broom, and (2) herbicides (i.e. terbuthylazine and hexazinone) that kill everything and have soil residual activity for a number of months afterwards to provide control of broom germinants.

To be successfully controlled under multiple (biological, ecological, scientific, economic, political, social and legal) dimensions (Anderson *et al.* 2000; Myers & Bazely 2003) with the first two levels have been mentioned in my study, ideally broom needs to be managed in an integrated system with combined effects from grasses, knockdown herbicides, and herbicide residues in the soil (Chapter 6). My results indicate that all herbicides used gave good control to old broom seedlings and killed further germinating broom seedlings (Chapters 4 and 5). Although low broom seedling emergence was relatively similar among the herbicide treatments, perhaps due to residual effects of herbicides, another reason preventing broom seeds from germination could be the high cover of logging debris present in quadrats before the application of herbicides and at least six months after treatment. Unfortunately, the ground covers established poorly in this trial, though there may have still been enough grass present in some areas to cause some suppressive effect. It seems that simply aerially sowing the seeds without fertiliser and without waiting sufficiently for the residual effects from metsulfuron-methyl to wear off does not result in good cover. Therefore, allowing the site to be covered with the debris as mulch might be a good way to minimize broom seeds germinating at least in the short-term, but this will also adversely affect grass establishment. I have developed models for assessing and predicting impacts of these herbicides on broom and indicating key stages that are most influenced by management options. Although these models are relatively simple and novel, they have shown that broom can develop rapidly from seeds to become large plants soon after germination in the absence of herbicide residues or suppression by grasses.

7.3 Recommendations for future research

Environmental considerations are starting to change the operating environment for herbicide use in plantation forestry in New Zealand. Meeting the goals of certification while retaining cost-effective vegetation control presents a challenge to the plantation forestry sector (Rolando *et al.* 2011b). Research on finding alternative management strategies for broom in New Zealand forests therefore should include some environmentally-friendly approaches.

The use of biological control agents such as the gall mite (*Aceria genistae*) as part of a management plan has been undergoing some investigation and some preliminary results have been obtained (Paynter *et al.* 2012). However, results have not been encouraging enough yet to allow it to be applied in forests where variability affects the rate of establishment of these agents (Affeld *et al.* 2004). Herrera-Reddy *et al.* (2012) assessed management options (biological control using seed weevil alone; biological control combined with mowing and biological combined with fire) to control the broom seed bank and found that the use of seed weevil alone was not successful in reducing healthy broom seed bank density with nearly 2500 seeds m^{-2} remaining after one year. Another potential control method might be the use of a bioherbicide formulated from the fungus *Fusarium tumidum* Sherb., a naturally occurring pathogen of broom and gorse (Morin *et al.* 1998; Fröhlich *et al.* 2000; Barton *et al.* 2003). This work is still on-going to improve the effectiveness.

The use of over-sowing grasses to suppress broom seedlings seems to be a more realistic non-chemical control measure but success is highly site-dependent, as shown in this thesis. Therefore, a proper scheduling of over-sowing grasses in forestry site could be improved with the applications of fertiliser and seed coating. The interesting finding that logging debris is able to suppress broom seedling from germinating (Chapter 6) suggests that it is better to keep the soil covered with a thickness of debris for some time with less restriction to establishment of grasses.

Grazing by sheep and cattle has been regarded as one of the traditional ways for weed control in many forests of the world including New Zealand (Adams 1975). In an European black pine stand (*Pinus nigra* Arn. subsp. *nigra*), goat grazing clearly affected the performance of a legume shrub *Genista scorpius* and posed no risk to the planted trees (Valderrábano & Torrano 2000). The timing of herbivory in relation to the phenological stage of *G. scorpius* was the most important factor affecting both the survival and regrowth rates and flowering performance. However, pine species are very palatable to sheep and thus these plantations are not recommended for sheep grazing treatments without a very experienced shepherd (Wiensczyk *et al.* 2011). Although livestock could eat broom, they cannot be used safely among pines within the first few year of growth.

In summary, although some alternate ways can be incorporated in a management plan for broom control, they are not feasible on their own without herbicides and/or ground covers. The reduced herbicides used in *P. radiata* plantation forests in New Zealand as required by forest certification criteria suggests that ground covers are probably the best option, but more trials need to be conducted. Using models like the ones in this thesis could assist in determining the effectiveness of the methods. Ecologists and managers should be more interested in complex models that include ecological, economic, and social variables to address problems regarding how methods are sustainably applied.

Such models have been developed for management of broom in natural systems (Odom *et al.* 2003). These, however, are out of scope of this project.

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