THE EFFECT OF PERENNIAL RYEGRASS (*Lolium perenne*) SOWING RATES ON WEED ESTABLISHMENT, AFTER ONE YEAR.

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Errata

Key: P = page; ln = line. Underlined characters signify inserted text; crossed out characters are replaced by underlined ones in the same line.

P.1, ln.14: cocksfoot (*Dactylis glomerata*) and timothy (*Phleum pratense*)

P.7, ln. 2: ~~This type of response~~ Plasticity of an individual

P.17, ln. 7: being dormant (Young 1985)

P.33, ln: indicated in Table 3.1. The tray experiment was a completely randomised design with uneven replication.

P.36, ln 8: 3.2.4. Data analysis. Data concerned with sowing rates was investigated using analyses of variance (ANOVA). Data related with ryegrass tiller counts was investigated using regression analyses.

P. 42, ln. 8: With Treatment 1 (0/0) removed a ~~A~~ linear regression was

P. 78: to be followed. Mapping was carried out using a sheet of acetate on a piece of glass that was positioned above the sub-plot. The position of each weed seedling in the sub-plot was marked onto the sheet of acetate. The same sheet of acetate was used at each count for that sub-plot, however a different coloured pen was used each time. This enabled the fate of existing seedlings to be checked and newly emerging seedlings identified as such.

P. 78: 4.2.3. Data analysis. Data concerned with sowing rates was investigated using analyses of variance (ANOVA). Data related with ryegrass tiller counts was investigated using regression analyses.

Abstract

Two trials were conducted to determine whether the weed control benefits of high sowing rates of perennial ryegrass (*Lolium perenne*) continued into the second year after sowing. Seeds of Scotch thistle (*Cirsium vulgare*), nodding thistle (*Carduus nutans*), ragwort (*Senecio jacobaea*) and hedge mustard (*Sisymbrium officinale*) were sown into established perennial ryegrass and white clover (*Trifolium repens*) swards both in trays and in the field, in late autumn. The emerging weed seedlings were mapped at intervals to enable their fate to be followed. In the trays, seedlings were mapped at four week intervals, and the experiment continued for four or five months, depending on the species. In the field, weed seedlings were mapped both before and after each grazing and the experiment continued for seven months.

The trays with low ryegrass sowing rates had a higher density of white clover than those trays with high ryegrass sowing rates. In the field plots with low sowing rates, both the broad-leaved weed population and volunteer grasses were more abundant than in the high ryegrass sowing rate plots. This resulted in the different treatments having a similar competitive ability against the sown weed seeds, one year after the swards were sown.

Both nodding thistle and Scotch thistle emergence was extremely low in the bare ground trays, probably relating to seed predation of these large seeds off bare soil. Scotch thistle and hedge mustard emergence were both reduced by high sowing rates of perennial ryegrass when compared to trays and field plots sown with white clover only. Nodding thistle and ragwort however provided some unusual results. Both of these species experienced an increase in total emergence as ryegrass sowing rate increased. With nodding thistle, this occurred in the field and with ragwort, in the trays. This obviously was unexpected but in reality the increases in emergence, although significant, were small and of little practical importance. The increases probably related to the similar competitive ability of the swards one year after pasture sowing. Emergence of ragwort in the field and nodding thistle in the trays was not affected by ryegrass sowing rate. For all species, in both the field and the trays, emergence was delayed as the sowing rate increased.

There was very low mortality in the tray experiment. Mortality was much higher in the field due to the effects of grazing animals and also the longer time frame of the field experiment. All hedge mustard seedlings that emerged in the field were killed, and only one nodding thistle seedling survived to the end of the experiment. With both Scotch thistle and ragwort, seedlings seemed to have a higher chance of surviving in the high density ryegrass treatments, probably due to the physical protection from grazing animals provided by ryegrass.

High mortality in the field experiment rendered seedling size data meaningless. In the trays, for all species, the heaviest seedlings were found in the treatments with either bare ground or where only clover was sown, indicating that competition from ryegrass had a serious negative effect on weed size. Weed size did not vary significantly as ryegrass sowing rate increased.

In conclusion it would appear that most of the weed control advantages from higher sowing rates of perennial ryegrass are obtained in the first year after sowing, as all swards that contain perennial ryegrass appear to have a similar competitive ability against invading weeds in the second year after sowing.

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Herby for constantly reminding me that as long as you've got a warm place to sleep and your food bowl is full, that really life ain't so bad.

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CHAPTER ONE

Introduction

In New Zealand and many other countries there is increasing interest in reducing the amount of pesticides used (Seefeldt & Armstrong 2000). As a result pesticide use in pastoral agriculture in New Zealand is static or declining after many years of increases (Holland & Rahman 1999). Although herbicides are still the most cost-effective technology for control of weeds (Holland & Rahman 1999), there is increasing demand for new technologies and management strategies to be developed to reduce the volume of chemicals used in pastoral agriculture.

Newly sown pastures are particularly sensitive to weed infestation. Herbicides are frequently used to control weeds, both before sowing and after emergence of the pasture species (Rahman *et al.* 1993). Cullen (1966) in a review of previous experiments at Invermay Research Centre commented on the importance of pasture species providing competition for weeds during pasture establishment. He indicated that perennial ryegrass (*Lolium perenne*) was a particularly aggressive species which could suppress slower growing grass species such as cocksfoot and timothy. Cullen (1966) also noted the potential advantages of weed suppression and increased herbage production in the first few months after sowing high rates of perennial ryegrass.

Studies in New Zealand have investigated high seeding rates of grasses to increase competitive pressure on weed seedlings during early pasture establishment. These experiments indicated that increased seeding rates of grass result in a reduction in the weed biomass present in the first year after the pasture was sown (Cullen & Meeklah 1959, Seefeldt & Armstrong 2000). However there is no research on the longer term effects of high seeding rates of grass on weed competition and therefore little is known of the long-term benefits (if any) of this weed control strategy. The experimental program which is reported in this thesis is building on the Seefeldt & Armstrong

(2000) study. However the issue under investigation is whether high ryegrass seeding rates continue to give increased weed control once the pasture has established. This study is particularly relevant to the organic industry where the option of using herbicides for weed control is not available.

1.1. Objective

The main objective of this study was to determine whether increased perennial ryegrass sowing rates had any effect on weed invasion once the pasture was established. This was studied by measuring the ability of common weed species to invade pasture swards that were established with different sowing rates of perennial ryegrass. The establishment of these weed species was investigated with both a tray and a field experiment which are described in Chapters 3 and 4 respectively.

Literature Review of Plant Competition, Pasture Establishment and Weed Biology.

2.1. Introduction

The concept behind high pasture seeding rates involves increasing the competition that the weeds experience during pasture establishment, reducing weed size, vigour, fecundity and survival. The following review covers the concept of plant competition, which is obviously highly relevant to this study. Aspects of pasture establishment are also reviewed as pasture management, seed germination and dormancy will influence the species present in the pasture and hence the competition exerted on emerging weed seedlings. The biology of the weed species involved in the study will also be reviewed, with particular emphasis on germination requirements, seed dormancy and previous studies involving these weeds and pasture competition.

2.2. Plant competition

Competition is defined by McKenzie *et al.* (1999) as the negative effect on growth, reproduction or survival that a plant has on another by consuming or controlling access to, a resource that is limited in availability. According to another definition, competition arises when two or more organisms seek a common resource whose supply falls below their combined demand (Deschenes 1973).

Interactions among neighbouring plants can strongly influence plant performance (Turkington & Jolliffe 1996), as the growth and development of a plant is often modified by the proximity of other plants. The result of competition is a reduction in both the rate and total amount of growth and sometimes even the survival of the competing organisms (Deschenes 1973).

Competition can be observed between individuals of the same species - termed intraspecific competition, or between individuals of different species, for example competition between weed species and sown pasture plants - interspecific competition (Gill & Davidson 2000). However, it is thought that intra-specific competition is stronger as the plants will be competing directly for the same resource, or as Clements *et al.* (1929) commented "competition is keenest when individuals are most similar".

2.2.1. Interference

Harper (1977) used the term interference to describe all changes in the environment brought about by the proximity of individuals. This includes:

- competition for resources (neighbour effects due to consumption of resources in limited supply),
- allelopathy (the production of toxins by one plant which influences another), and
- facilitation (whereby one plant species benefits through the presence of another species).

2.2.1.1. Competition for resources

The resources that are most commonly associated with plant competition are mineral nutrients, light and water. This type of competition only occurs when the demand for a particular resource exceeds the availability and so competition for resources varies throughout the year as the supply/demand ratio changes. Competition from weeds in a pastoral situation can decrease the essential resources available to the sown pasture plants resulting in a decrease in "useful productivity" from the land.

Species or individuals with larger or more effective root systems are likely to absorb a greater share of the available nutrients. The process of nutrient uptake requires the nutrient ions to move to the roots mainly by the process of diffusion. Low nutrient mobility can decrease the level of competition, as only the very closest roots will have access to the nutrient source. The more mobile the nutrient ions, the larger the depletion shell will be around the root and therefore there is an increased likelihood that competition will occur. Competition for nitrate ions is more common than for phosphate or potassium ions due to its higher mobility in the soil (Gill & Davidson 2000).

The level of nitrogen in the soil has been shown to significantly influence the competition between two annual pasture grasses *Hordeum leporinum* and *Lolium rigidum*. *Lolium* was found to grow faster than *Hordeum* at high nitrogen, as its faster growth rate and greater stature enabled it to intercept more light. However, at low levels of nitrogen the growth rate of both species was severely restricted. In this situation *Hordeum* became the better competitor as its faster germination and larger seedling size enabled its roots to explore the soil more rapidly and absorb the available nitrogen (Cocks 1974).

Taller growing or faster establishing species can reduce the amount of light available for other species present in the sward. The quantity and quality (ratio of red/far-red wavelength) changes as light passes through the canopy (Gill & Davidson 2000), thus giving an advantage to plants forming the canopy layer.

The competitive ability of individual plants is directly affected when water is in limited supply. However, when moisture levels in the soil are high competition between species may also be affected as surplus water may suit one species over another. Indirect competition relating to water moisture levels has been observed in reed canary grass (*Phalaris arundinacea*) which benefited due to the poor growth of other species in soil ranging from moist to inundated with water (Morrison & Molofsky 1998).

When soil moisture is limiting, many weed species may dominate as they are better able to grow in the dry conditions than pasture plants due to deep tap roots. Plants with a C_4 photosynthetic pathway use water more efficiently than C_3 plants (McKenzie *et al.* 1999) and therefore gain a competitive advantage when soil moisture is limiting.

2.2.2.2. Allelopathy

Sown pasture species may be negatively affected through allelopathic chemicals released by weed species. Putman (1985) defines allelopathy as the detrimental chemical effects of higher plants of one species on the germination, growth or development of plants of another species. The detrimental effect is exerted through release of a chemical by the donor species. Allelochemics can be released from plant tissues in a variety of ways, including volatilisation, root exudation, leaching and decomposition of the plant residues (Putnam 1985).

Virtually all plant tissues contain chemicals with allelopathic potential. However, whether these chemicals are present in sufficient quantities or concentrations to have a negative effect on another plant is the critical question (Putnam 1985). The active ingredients involved in allelopathy are not well known however, as conclusions of allelopathic effects are usually based on the activities of plant extracts or residues (Gill & Davidson 2000). Much of the research into allelopathy has been conducted in controlled environment conditions i.e. glasshouse or petri dish. It is not known whether these negative effects will still be apparent in a field situation where toxins could be adsorbed onto soil particles or degraded by soil microbes (Gill & Davidson 2000) or are simply present in a less concentrated form.

2.2.2.3. Facilitation

Facilitation is a process where the close proximity of another species (e.g. a weed species) can be beneficial. It has been shown in experiments to operate in a variety of ways e.g. ameliorating harsh environmental characteristics, altering substrate characteristics, increasing the availability of a resource, or by eliminating potential competitors. Facilitation mechanisms may act simultaneously with resource competition or allelopathy and the overall effect of one species on another may be the product of multiple complex interactions (Callaway 1995).

2.2.2. Responses to competition

When individuals of a species are released into a favourable environment their numbers increase rapidly at first and then settle down to a population size that is relatively stable compared with the increases that are theoretically possible. There are three main methods by which plants respond to increasing density to regulate population size: plasticity of an individual, density dependent mortality (Harper & Gajic 1961) and self-controlled germination (Deschenes 1973).

2.2.2.1. Plasticity of an individual

This type of response confers on the population the properties of self-regulation by allowing a rapid increase in size of individuals at low densities but places restrictions on growth, as the density becomes greater (Harper & Gajic 1961). The effect of plasticity can be seen either in the reproductive capacity of individuals, or in the rate of vegetative production per individual. These plastic responses of individual plants may combine to give an asymptotic relationship, with a constant final yield per unit area irrespective of the density of plants (Holliday 1960, Harper & Gajic 1961). Alternatively an overcompensating response may occur whereby a parabolic final yield curve is found, where a certain population density gives a maximum yield which is decreased at higher or lower densities (Clements *et al.* 1929; Hodgson & Blackman 1956, Holliday 1960).

Reproductive plasticity refers to a situation where the amount of seed produced per unit area is constant irrespective of the density of plants present. An example of reproductive plasticity can be seen through experiments with *Agrostemmma githago.* The seed output from pure stands of *A. githago* appears to be largely independent of the number of seeds sown. *A. githago* responded to increased density through a reduction in the number of capsules per plant and a reduction in the number of seeds per capsule (Harper & Gajic 1961). Palmblad (1968) discovered very similar results with the weed species shepherd's purse (*Capsella bursa-pastoris*). The number of seeds produced by an individual at low density was in excess of 23,000 seeds, but a plant of similar genotype under high density produced only 210 seeds.

The perennial species studied by Palmblad (1968) did not necessarily exhibit the same reproductive plasticity that is common among weedy annuals. For example, narrow leaved plantain (*Plantago lanceolata*) produced an average close to 2,200 seeds per plant in low density plantings compared to about 30 seeds per plant at high densities. This severely reduced the reproductive capability of the species in that season as over 90% of the plants examined remained in a vegetative state at densities exceeding 850 plants/m^2. However, just to prove that every species is unique and broad generalisations can be dangerous, Palmblad (1968) also found that the perennial broad-leaved plantain (*Plantago major*) produces a considerable amount of seed at every density and less than a third of the individuals remained vegetative at high densities.

The typical relationship between population density and vegetative yield is an asymptotic relationship. Weight per plant increases as plant density increases up to a critical point whereby any further increases in density result in competition and a resulting decrease in weight per plant (McKenzie *et al.* 1999). This critical point where vegetative production plateaus is species specific (Palmblad 1968).

Palmblad (1968) investigated the effect of different sowing densities on nine weed species and found that all species increased in dry weight production of vegetative material with increasing density up to a point where production levelled off. Holliday (1960) also found similar results with crop species. He discovered that increasing the sowing rate of Essex giant rape past 16 tons/acre gave no significant advantage in increased dry matter yield per acre. However, the total number of plants present increased as sowing rate increased but the dry matter yield per individual plant decreased substantially, thus indicating a large amount of vegetative plasticity of the individual plants.

At low sowing densities *Agrostemma githago* individuals tend to be much more variable within the population, with a wide range of plant sizes. As densities increase plant sizes decrease but also become less variable, with multi-branched plants being either rare or absent (Harper & Gajic 1961).

Different species provide different levels of competition for another species. For example, Harper & Gajic (1960) found that *Agrostemma githago* suffered only initially through competition with sugar beet due to a similar growth form and emergence time but quickly outgrew the influence of the prostrate sugar beet. In contrast, *Agrostemma* was directly influenced from the seedling stage by wheat which went on to dominate the situation and affected the plasticity of *Agrostemma* throughout its lifecycle.

Plasticity might be considered as a means by which a considerable number of genotypes can be preserved in a population. In contrast, mortality tends to reduce the number of genotypes present in the breeding population (Palmblad 1968).

2.2.2.2. Density dependent mortality

Density-dependent mortality occurs as plants grow due to the limited amount of leaf area that can be maintained by a particular environment. Smaller plants or tillers will die if a positive carbon balance cannot be maintained due to competition for resources from neighbours (McKenzie *et al.* 1999). This response is such that increased population density reduces the chance of survival for a particular individual (Harper & Gajic 1961).

Yoda *et al.* (1963) were the first to formally analyse density dependent mortality. In experiments involving overcrowded pure populations of several species they discovered that the number of surviving plants in a population was related to their mean weight. This therefore indicates that there is only a certain amount of biomass that can be supported by any environment; i.e. $w=cp^{-3/2}$ where w = mean dry weight per plant, p=density of surviving plants and c is a constant that varies depending on the species. This relationship is often referred to as the -3/2 power law.

An example of density dependent mortality can be seen in broad-leaved plantain. When this weed was grown at high densities (11,000 seeds/m^2 sown) in a pure stand, 24% of the emerging plants died, compared to a 7% death rate at lower densities. In the same experiment *Silene anglica* experienced no mortality at any density (Palmblad 1968), indicating that density related effects are very species specific.

2.2.2.3. Self-controlled germination

Self-controlled germination involves the suppression of germination with increasing seed sowing densities (Palmblad 1968). Its effect is to limit the number of plants per unit area (Deschenes 1973). This response could lead to lower weed emergence rates when pasture sowing rates are increased.

Palmblad (1968) found examples of self-controlled germination in three weed species that were sown at high densities in pure stands. His results show that the germination of *Bromus inermis* fell from 87%, at a sowing rate of 275 seeds/m^2, to 52% at a sowing rate of 11,000 seeds/m^2. In the same experiment *Conzya canadensis* germination rate fell from 87% to 52%, and *Silene anglica* from 73% to 35%.

Lonsdale & Watkinson (1982) also discovered what they termed negatively density dependent seed germination. At sowing densities of 300,000 perennial ryegrass seeds/m^2 only 45% of the seeds germinated, compared to 95% at 1000 seeds/m^2.

Mechanisms that have been put forward as responsible for the reduction of germination at high densities include an inhibitor released from the seeds (Linhart 1976), carbon dioxide production from roots of germinated seedlings inhibiting subsequent germination (Inouye 1980) and desiccation of seeds as a result of soil capping i.e. germinated seedlings may lift up portions of the soil surface containing ungerminated seed (Lonsdale & Watkinson 1982).

2.3. Pasture establishment

Large areas of permanent pasture are resown annually in New Zealand, often to replace plants damaged by pests, drought or disease (Clough & Hay 1993). A survey carried out in 1981 indicated that both dairy and sheep farmers resow about 6% of their holdings each year (Sangakkara *et al.* 1982). During the establishment phase, pasture seedlings are particularly vulnerable to competition from more vigorous weed species and therefore the period from sowing until the pasture is fully established is of great importance with respect to weed control. Pasture establishment has two major components: seed germination and seedling growth.

The primary goals of pasture establishment are to obtain rapid establishment of the sown species, to ensure the survival of all of the sown species, and to begin dry matter production as quickly as possible (Hampton *et al.* 1999). If pasture species establish quickly and can form a canopy within a short space of time then the sown species are in a better situation to out-compete potential weed invaders and gain maximum use of available resources.

2.3.1. Management factors influencing successful pasture establishment

Sward establishment may take up to a year depending on environmental conditions and the management. Management decisions about pasture species and cultivars, seed type, sowing rate, pesticide application, grazing management and fertiliser application will strongly influence the success of pasture establishment and the extent of the resultant weed population.

2.3.1.1. Pasture species

The pasture species most suitable for a particular situation depends on four major factors of the site: temperature, soil moisture, soil fertility, and pasture management (Hampton *et al.* 1999). The choice of pasture species is critical as an inappropriate species may not grow sufficiently well to out-compete volunteer weeds emerging from the seed bank. For example, perennial ryegrass is a key grass in the New Zealand pastoral industry because of its ability to establish rapidly, and its high productivity in medium to high fertility situations. In contrast, cocksfoot (*Dactylis glomerata*) is more suited to low to medium fertility situations in summer dry areas because it experiences growth peaks in summer. However, this advantage must be weighed up against its poor winter growth (Clough & Hay 1993).

For each pasture species there are a range of cultivars that have been created through plant breeding. A cultivar is a group of plants that have been specifically bred for a certain characteristic (or characteristics). These distinctive characteristics are retained when the plant reproduces and so plants of a particular cultivar are distinguishable from other groups of plants belonging to the same species (Hampton *et al.* 1999).

An example of cultivar differences can be seen in node characteristics of the white clover cultivars Grasslands Tahora and Grasslands Kopu. Tahora (which was bred for use in heavily grazed swards) has a significantly higher node production rate, a higher proportion of nodes branching, shorter petioles, thinner stolons and a lower proportion of flowering nodes than Kopu (Caradus & Chapman 1991).

2.3.1.2. Seed quality

To ensure a high rate of seedling establishment it is crucial to start with high quality seed. Seed quality is determined by seed properties that affect how well plants establish. These include species and cultivar purity, uniformity, seed weight, amount of weed contamination, seed health, presence of pests or diseases, and desirable performance based indicators such as germination, vigour, moisture content, seedling emergence and storability (Clough 1993, Hampton *et al.* 1999).

For example, the size of the seed may give a competitive advantage to the developing seedlings (Risser 1969), and allow it to compete better against emerging weed seeds. Experiments with subterranean clover (*Trifolium subterraneum*) indicated that when a mixed sward of large seeds and small seeds were sown, seedlings resulting from large seeds had an initial advantage that compounded so rapidly so that after 84 days these plants were intercepting 98% of the available light (Black 1958). In another experiment involving subterranean clover, Davidson & Donald (1958) discovered that the first mortalities in their experiment involved the individuals which emerged from small seeds.

2.3.1.3. Herbicide application

Early weed competition can greatly affect the successful establishment of a new pasture. Spraying herbicides, both pre- and post-sowing, to control emerging broadleaf weeds in new pasture is generally recommended to prevent the establishment of weed infestations. Chemicals commonly used at this stage in pasture establishment are the phenoxy-butyric herbicides, 2,4-DB and MCPB due to the minimal damage that these chemicals inflict on emerging grasses and clovers (Rahman *et al.* 1993).

2.3.1.4. Sowing rate

The sowing rate of pasture plants differs depending on land use and the type of country. Grasses in dairy pastures are recommended to be sown at rates between 5-10 kg of seed/ha, and white clover at 3-4 kg/ha (Clough & Hay 1993). However, actual sowing rates in use are typically higher than strictly necessary due to the relatively low cost of seed and the fear of failure due to environmental stresses (Hampton *et al.* 1999).

There has been increasing interest in reducing pesticide use in pastoral systems. Recent studies have investigated the benefits of sowing higher rates of grass seed to increase competition for emerging weeds in establishing pasture in an effort to reduce the need for herbicides at this stage in pasture development. Seefeldt & Armstrong (2000) investigated the effect of different sowing rates of perennial ryegrass on the establishment and growth of Californian thistle (*Cirsium arvense*), Scotch thistle

(*Cirsium vulgare*), hedge mustard (*Sisymbrium officinale*), ragwort (*Senecio jacobaea*) and nodding thistle (*Carduus nutans*). They discovered that although weed emergence was unaffected by the perennial ryegrass sowing rates, both survival rates and individual weed weights were significantly lower in treatments with high density ryegrass.

In an earlier study, Cullen & Meeklah (1959) found that treatments with a high seed rate of perennial ryegrass suppressed most of the volunteer weeds. However the high perennial ryegrass rates also suppressed the slower establishing grasses (i.e. cocksfoot and timothy (*Phleum pratense*)) which were sown at the same time. Suppression of other sown pasture species is an obvious disadvantage to sowing high seeding rates of perennial ryegrass. However, White (1977) has suggested that higher rates may be beneficial where there is likely to be a high weed population, where rapid early production is essential or where ryegrass dominance is required for seed production.

2.3.1.5. Grazing management

Newly established seedlings are usually ready to graze when 10-12cm high and tillering has begun. The objective of this early grazing is to encourage tillering of grasses, prevent fast-establishing species shading out slower growing species, to control weeds, and to consolidate cultivated soil (Hampton *et al.* 1999).

Damage to plants by grazing animals can create gaps in the pasture sward. These gaps are then colonised by either clonal spread by edge plants or through establishment of seedlings from the seed bank (Bullock *et al.* 1995). Intense grazing creates more gaps than lax grazing, allowing more opportunities for fast growing weed species to establish.

Grazing animals may show a preference for a particular species (Bullock & Marriott 2000) which may give less palatable species (i.e. weeds) an advantage over the sown pasture species. The removal of herbage through grazing may also affect the competitive environment by enabling light to penetrate the canopy. As light becomes less limiting, nutrient and water competition may become more important (Bullock 1996).

2.3.1.6. Fertiliser application

In low fertility situations, small amounts of nitrogen (20-30kg/ha) can significantly boost the establishment of grass species if sown onto cultivated soil. However, the application of fertiliser when overdrilling into existing pasture will only serve to encourage the growth of the established pasture plants that will provide even more competition for the emerging seedlings (Hampton *et al.* 1999).

The fertility of the soil can have a large effect on the ensuing competition in the establishing sward. White & Harper (1970) investigated the effect of soil fertility on different seeding densities of pure and mixed stands of rape (*Brassica napus* L.) and radish (*Raphanus sativus* L.). They discovered that a greater amount of thinning occurred on the more fertile soils. This may occur as higher fertility allows the seedlings that germinate first to grow quickly and attain a larger size than would occur on less fertile soil. Any environment can only support a fixed amount of vegetation due to the constant source of light; therefore in a high fertility situation there will tend to be a smaller number of large plants present.

2.3.2. Seed germination

To reduce the impact of weeds on an establishing pasture, sown pasture seeds must germinate quickly. Seed germination is primarily affected by temperature, moisture, soil structure, vegetation gaps and dormancy. These factors affect the germination of both sown pasture species and volunteer weed species, although the importance of each factor is species specific.

Pastures are typically resown in autumn regardless of locality as at these times temperature and moisture levels are the most conducive for seed germination and seedling survival (Sangakkara *et al.* 1982).

2.3.2.1. Temperature

Slow seed germination due to low temperatures increases the amount of time that the seed is subject to attack from soil fauna and fungi. Reduced germination rates will lead to poor establishment of pasture under cool conditions (Hampton *et al.* 1999).

Hill & Luck (1991) showed that lower rates of germination result from low temperatures after sowing. They tested the germination of pastoral legumes at different temperatures under laboratory conditions. The five temperature ranges studied fluctuated on 12 hour cycles and were 1.) 24°C and 20°C; 2.) 20°C and 15°C; 3.) 15°C and 10°C; 4.) 12°C and 6°C; and 5.) 8°C and 2°C. When exposed to the four highest ranges white clover (*Trifolium repens*) had a germination rate of 96%+. However, this decreased somewhat in the coldest range where only 83% of the seed germinated. Similarly, strawberry clover (*Trifolium fragiferum*) had over 90% germination at the first four temperature ranges and only 74% at the coldest temperatures. The differences were even more dramatic with *Lotus pendunculatus* which recorded 97%+ germination at the three warmest temperatures, 48% at the fourth and no germination whatsoever in the coldest treatment.

2.3.2.2. Water

Soil moisture must be adequate to start the germination process and also to support the continued growth of the seedlings. However, excess water in the soil profile can reduce the likelihood of seedling survival by replacing air in the soil pores, causing anaerobic conditions in the soil. Anaerobic respiration by the seed leads to an accumulation of toxic metabolites and can result in death of the seedling (Hampton *et al.* 1999).

Earhart & Fugua (1979) found that germination of watermelon (*Citrullus vulgaris*) was suppressed when seed was exposed to both 5% moisture (soil air dry) and 29% water (soil saturated). They attributed these results to a lack of moisture at the 5% moisture and a lack of available oxygen at the 29% level.

2.3.2.3. Soil structure

Poor soil structure and loss of aggregate stability can reduce oxygen diffusion to the seed, through reduced pore space and a subsequent increased risk of pores becoming water filled. A lack of good soil structure can also provide a mechanical constraint to emerging seedlings. This is particularly evident on silty clay and loam soils that can develop soil crusts or caps when drying after heavy rain (Hampton *et al.* 1999).

Soil structure also affects the number and condition of available germination sites which can subsequently affect the eventual population size (Risser 1969). Harper (1961) experimented with *Bromus rigidus* and *B. madritensis* seed germination in pots in which the soil surface was either rough, or had been wetted and allowed to dry and crack. He found that rough soil provided more sites for germination and therefore the population increased as the number of seeds sown increased. In contrast, the smooth, cracked soil surface provided few ideal sites for germination and therefore, a maximum number of emerging seedlings was soon reached and any increase in the seeds sown failed to result in an increase in the number of seedlings emerging.

2.3.2.4. Vegetation gaps

Many plants (especially weeds) depend on the creation of gaps in perennial pasture for opportunities to invade the pasture. In pastures, gaps may arise through the action of various agents (e.g. stock treading) which weaken or kill established plants (Panetta & Wardle 1992). The size of a gap is very important as size controls the amount of physical space available for colonization and also the level of light reaching the soil surface and the levels of nutrients and moisture available (Goldberg & Werner 1983).

Panetta & Wardle (1992) investigated the effect of different sized gaps on seedling emergence of three clover species and broad-leaved dock (*Rumex obtusifolius*). Their experiment indicated that although emergence of the clover species (*Trifolium repens*, *T. subterranean* and *T. pratense*) was greatest in the bare ground plot, broad-leaved dock had its highest emergence rate in gaps of 6cm diameter.

Temperature fluctuations and differing moisture content could explain the decrease in weed emergence in bare ground plots (as opposed to gaps) (Panetta & Wardle 1992). Thompson *et al.* (1977) examined the effect of temperature fluctuations on seed germination and discovered that when maintained in darkness, seeds of some species would only germinate when subject to fluctuating temperatures. The same study indicated that such fluctuations were greatly enhanced within gaps created in grassland vegetation. Decreased weed emergence in some of the larger gaps or on bare ground may be a result of faster drying of the soil surface after rainfall owing to greater exposure (Panetta & Wardle 1992).

2.3.3. Dormancy

Seed germination may be affected by dormancy. Dormancy enables a seed to delay germination until conditions are such that the likelihood of survival for the seedling is increased, e.g. germination could be delayed until a vegetation gap opens up above the dormant seed.

At any time the number of weed seeds in the soil seed bank down to ploughable depths is generally in the range 10-20,000 seeds/m^2, the majority of these being dormant. However, these seeds will germinate sporadically over time as their dormancy breaking conditions are met. The dormancy of many seeds is broken on exposure to light, hence the flush of weed seedlings after cultivation. Consequently the soil seedbank acts as a continual source of competing plants in agricultural systems (Young 1985).

There are three main types of dormancy of seeds: innate dormancy, induced dormancy and enforced dormancy (Anderson 1996).

2.3.3.1. Innate dormancy

Innate dormancy exists when seed is shed from a plant in a dormant state (Young 1985). The seed is in a viable state however it is prevented from germinating when exposed to favourable conditions by some property of the embryo, associated endosperm or maternal structures (Harper 1977).

There are four types of innate dormancy:

1.) Incomplete development of the seed - development continues once the seed is shed which imposes a time lag between dispersal and germination.
2.) Biochemical trigger – e.g. germination is controlled by photoperiodically or temperature operated triggers.
3.) Chemical inhibitor - i.e. germination may be triggered once a chemical inhibitor has leached from the seed.
4.) Genetic control of innate dormancy - this is indicated by the ability to breed plants without dormancy (Harper 1977).

2.3.3.2. Enforced dormancy

This is the inability to germinate due to an environmental constraint (unfavourable conditions) i.e. shortage of water, low temperatures, poor aeration, (Harper 1977), or with inappropriate light. For example, *Bromus sterilis* exhibits enforced dormancy when exposed to direct light as most seed of this species will only germinate in the dark (Peters *et al.* 2000). This mechanism ensures that seed of *B. sterilis* will only germinate when covered by a layer of soil.

2.3.3.3. Induced dormancy

This is an acquired dormancy where the inability to germinate is caused by conditions experienced after the seed has been shed (Harper 1977, Young 1985). Such seed will remain dormant even if conditions become suitable for germination and will only germinate once this secondary dormancy has been broken. Induced dormancy often occurs as a response to the burial of seed (Young 1985).

2.4. Biology of weeds in experiment

The previous sections of this literature review have outlined plant competition, pasture establishment and seed germination in general. In this section the weeds involved in this particular study will be reviewed. Special attention is given to the germination requirements of the weeds and also previous studies on the effect of pasture competition on these weed species as these factors have particular relevance to the current study.

2.4.1. Hedge mustard (*Sisymbrium officinale*)

Hedge mustard is common and widespread throughout all of New Zealand including offshore islands. It originated from central and southern Europe, north-west Africa and Asia minor (Roy *et al.* 1998).

It is a leafy annual herb with deeply lobed leaves on long stalks that form rosettes of 15-30cm in diameter. Rosette leaves are deeply lobed, with the largest lobe at the end of the leaf. Wiry flowering stems up to 1m tall branch extensively and support numerous small

(3mm diameter) pale yellow flowers (Taylor 1980, Roy *et al.* 1998). Stems are bristly with downward directed hairs (Ivens & Taylor 1985).

Hedge mustard is primarily a weed of gardens, hedgerows and fence lines. This weed can also be found in cropping systems and cattle-grazed pasture as cattle seem reluctant to graze this weed (Taylor 1980, Ivens & Taylor 1985).

2.4.1.1. Germination of hedge mustard

The germination of hedge mustard seeds is affected by both nitrate and light levels. Bouwmeester & Karssen (1989) tested the effect of potassium nitrate on the germination of hedge mustard seed. The nitrate solution had a positive effect on germination in light conditions, its main effect being a delay in the onset of secondary dormancy after seed burial. However, in dark conditions the nitrate solution had a minimal positive effect on germination, indicating that the stimulating effect of nitrate required the simultaneous presence of both light and nitrate. Experiments by Karssen & De Vries (1983) also indicate that the combined action of nitrate and light is required to stimulate germination, in secondarily dormant hedge mustard seeds.

The actual concentration of nitrate within the seed can also affect the germination of hedge mustard. Hilhorst (1990) discovered that endogenous nitrate is a limiting factor in the light-induced germination of hedge mustard seeds in water. He found that seeds that contained less than 100 nmol/g nitrate did not germinate in either light or dark conditions.

Bouwmeester & Karssen (1989) tested the dormancy patterns of hedge mustard through germination tests after varying lengths of seed burial. They discovered that prior to seed burial germination was absolutely light dependent. However, hedge mustard seed lost this dependency on light after three months of burial, and close to 100% of the exhumed seed then germinated in dark conditions. After five months of burial, secondary dormancy set in and germination under both light and dark conditions was less than 5%.

Desiccation of hedge mustard seeds prior to testing enhances germination. This is thought to be due to a dormancy breaking effect, rather than desiccation being a requirement for germination. However, it could be assumed that desiccation of the seed is more likely to occur on a bare soil surface therefore this response might be a factor enabling seeds to detect gaps in the vegetation (Bouwmeester & Karssen 1989).

2.4.1.2. Effect of pasture competition on hedge mustard

Very little is known about the effect of pasture competition on hedge mustard. Seefeldt & Armstrong (2000) investigated the effect of increased perennial ryegrass sowing densities on the emergence, growth and development of hedge mustard. No differences were observed in seedling emergence rates over the ryegrass densities. However, within fifty days of sowing, the ryegrass plants had begun to exert significant pressure on the hedge mustard seedlings. The taller ryegrass plants reduced the growth rate of the seedlings as a function of ryegrass seeding density. Small initial differences in weed dry weight translated to much larger differences over time. Hedge mustard was less affected by the higher ryegrass densities than more prostrate weeds although the effect was still large. Hedge mustard may have avoided some competition effects as its leaf shape permitted it to grow through the ryegrass canopy.

2.4.2. Scotch thistle (*Cirsium vulgare*)

Scotch thistle is native to Europe, western Asia, Africa and the British Isles (Hulten & Fries 1986). It occurs in cool-temperate zones and warm-temperate and subtropical zones (Klinkhamer & de Jong 1993). It has been introduced into New Zealand, North America, Chile, and Australia and is now widespread throughout New Zealand (Roy *et al.* 1998)

Scotch thistle is typically a biennial or short-lived monocarpic herb. In the juvenile phase individuals form a single rosette with a taproot to 70cm and obovate-lanceolate prickly leaves (Klinkhamer & de Jong 1993, Mitch 1998). Estimates of rosette size vary from up to 65cm in diameter (Mitch 1998) to 1m (Hartley 1983) and may vary with environment. The larger rosette size was measured in New Zealand conditions. Rosettes tend to bolt in the spring of their second year, sending up flowering stems of 1-2m in height (Forcella & Wood 1986, Roy *et al.* 1998). Plants can bear between 10-200 flowering heads and therefore seed production can vary enormously but average values are around 2000-9000 seeds per plant (Forcella & Wood 1986). Seeds are equipped with a pappus for wind dispersal (Mitch 1998); although just over 10% of seeds reach dispersal distances of 32m or more. Average dispersal is between 50 and 150cm away from the parent plant (Klinkhamer *et al.* 1988)

The genus *Cirsium* is well known for its flavonoids. These are feeding attractants or deterrents and may be toxic especially to insects. Phenolic acids have also been identified in Scotch thistle and may serve as defensive or allelopathic agents (McGowan & Wallace 1972).

The spiny stems and leaves of Scotch thistle make it unpalatable to most livestock (Klinkhamer & de Jong 1993), and so once it establishes in a pasture it can grow unhindered by grazing animals. Rosettes can reach a large size 4which subsequently reduces the amount of pasture available for livestock (Hartley 1983). Dense stands of Scotch thistle can become impenetrable by livestock and even after senesence the spiny skeletons can remain standing and thus continue to obstruct animal movement and lower wool quality (Forcella & Wood 1986). Hartley (1983) found that a density of one Scotch thistle per m^2 was enough to reduce the spring/summer liveweight gain of sheep by an average of 2kg per animal.

2.4.2.1. Germination of Scotch thistle

Groves & Kaye (1989) investigated the temperature requirements for the germination of fresh Scotch thistle seed. The optimum range for germination was found (with a diurnal fluctuation of 10°C) to be between 15°C/5°C and 30°C/20°C. Germination decreased substantially both above and below these temperatures. This agrees with the findings of Grime *et al.* (1981) who found the optimum temperature for germination of Scotch thistle is 10-30°C.

Scotch thistle seeds have little innate dormancy and therefore germinate rapidly after imbibition (Forcella & Wood 1986, Klinkhamer & de Jong 1993). For this reason Scotch thistle is generally thought to have no persistent seed bank (Klinkhamer & de Jong 1993). However, dormancy can be induced if imbibed seeds are kept in the dark or if the red/far red light ratio is below about 0.5 (Grime *et al.* 1981). Doucet & Cavers (1996) also found that repeated wetting and drying of seed could reduce the germination rate of Scotch thistle seeds significantly, without affecting seed viability.

In a later study, Doucet & Cavers (1997) discovered that although fresh Scotch thistle seed can germinate in light/dark or dark conditions, some seed can aquire a light requirement for germination when imbibed at 5°C in darkness. In the field, this induced dormancy would prevent seeds from germinating when buried or located in deep shade.

C. vulgare can form a large persistent seed bank if seeds are buried to 15cm depth. Doucet & Cavers (1996) buried Scotch thistle seeds at a range of depths to investigate seed viablity over time. They found that seed buried at 15cm depth had a significantly higher viability once exhumed than those buried at either 3cm depth or on the surface. These differences were apparent over a period of six months to two and a half years. The differences could relate to the negligible temperature fluctuations at depths of 15cm or greater (Fenner 1985).

2.4.2.2. Effect of pasture competition on Scotch thistle

Dense populations of Scotch thistle often occur in heavily grazed pasture whereas it is uncommon on ungrazed land. This suggests that this weed is highly sensitive to interference from other pasture species (Forcella & Wood 1986). In many habitats Scotch thistle seedlings are out-competed by grasses or dicotyledons and the persistence of the population depends on new plants establishing in local disturbances and bare ground (Klinkhamer & de Jong 1993).

Bullock *et al.* (1994) discovered that survival of Scotch thistle seedlings and rosettes was increased under increased grazing in particular seasons. The reduction in interspecific competition is the most likely reason as the pasture species were grazed preferentially while the thistles were avoided (Bullock *et al.* 1994).

In a three year study, Forcella & Wood (1986) investigated the differences between Scotch thistle emergence and growth in sheep grazed plots versus ungrazed plots. They found that seedling emergence in the grazed plots equated to 10% of the seeds sown, compared with 15% in the ungrazed plots. However, by the end of the first year, thistles in the grazed pasture weighed more, produced more flower heads and more seeds per head than those in the ungrazed pasture. After two years the number of rosettes present in the grazed pasture was considerably higher than that in the ungrazed pasture.

Regardless of the grazing regime Forcella & Wood (1986) discovered a very low survival rate for Scotch thistle seedlings. Despite the damaging effects of sheep grazing (treading etc) seedling survival in the grazed pasture was generally higher than its ungrazed counterpart. Only 1% of the seedlings present in the grazed pastures resulted in rosettes whereas in the ungrazed pasture survival rates were even lower at 0.2%. Survival rates for rosettes are also not particularly high. Klinkhamer & De Jong (1993) found that the death rate of rosettes was inversely related to rosette size and varied between 10 and 69%.

In a grazing experiment, Bullock *et al.* (1994) found that winter grazing, spring grazing and harsh summer grazing all tended to increase Scotch thistle population size. Winter grazing and harsh summer grazing increased seedling survival. The grazing treatments affected conditions at the soil surface, increasing the number of bare sites, decreasing the number of sites with plant litter while having no effect on the number of sites covered with stems of pasture plants. Seedling emergence was greatest on sites with bare soil (30.5%), medium on sites with pasture plant stems present (21.2%) and least under plant litter (5.0%). They therefore postulated that grazing in winter or harder grazing in summer increased emergence by increasing the amount of bare ground.

A study by Panetta & Wardle (1992) indicated that the emergence of Scotch thistle was significantly higher in gaps with a diameter of 2 cm than was observed in plots with either no gap (i.e. 0 cm) or a completely bare ground plot. After five weeks, all of the seedlings that emerged in the bare ground plots and the 0 cm gaps were dead and less than 40% of those that emerged in the other gaps (2 cm, 6 cm and 10 cm) were still alive. After 27 weeks, the only survivors were found in the 6 cm gaps.

2.4.3. Nodding thistle (*Carduus nutans*)

Nodding thistle originates from Europe, north-west Africa and Asia minor (Roy *et al.* 1998). It was first noted in New Zealand in eastern Otago in 1899 and was only considered a local problem until the 1950s when it began to spread rapidly, although nodding thistle was present in Hawkes Bay several decades earlier It only became prominent after a series of dry summers in the early 1950s (Featherstone 1957). Nodding thistle is now a major and widespread pasture weed, especially in Otago, Canterbury, Hawkes Bay, and the central North Island pumice country (Ivens 1979, Popay & Thompson 1979, Popay & Medd 1990).

Nodding thistle is a biennial thistle, although is occasionally acts as an annual, depending on growing conditions. It forms a rosette of dark green leaves, up to 18 cm long and 10 cm wide. The leaves are deeply divided into triangular lobes with spiny tips 5-8 mm long. The flowering stem can measure up to 75 cm tall and supports red-purple, solitary 'nodding' flower heads (Roy *et al.* 1998).

Established bolting and flowering nodding thistles take up a lot of pasture space (Roy *et al.* 1998) and so are very effective in inhibiting pasture growth (Thompson *et al.* 1987) and restricting stock access to pasture.

Since the 1980s herbicide resistant forms have been discovered in Hawkes Bay and other areas (Roy *et al.* 1998). For example, Harrington & Popay (1987) reported a population of nodding thistle in Hawkes Bay required five times the normal rate of herbicide (MCPA) to kill them compared to a susceptible population.

2.4.3.1. Germination of nodding thistle

Nodding thistle seed experiences a period of innate dormancy lasting several weeks, immediately after being shed (Popay *et al.* 1987) however, if they become buried or covered with a dense sward they can remain dormant for long periods (Popay & Thompson 1979). The seed exhibits a phytochrome response, requiring light for germination (Medd & Lovett 1978), which may explain the occurrence of thistles in bare patches in pastures (Sindel 1991).

Groves & Kaye (1989) investigated the germination of fresh nodding thistle seed over a range of temperatures. Temperatures tested involved a 10°C diurnal fluctuation with the highest temperature being experienced by the seed for eight hours. The optimum temperature for germination was found to be 30°C/20°C and under these conditions over 95% germination was observed. Germination of over 60% was observed between 15°C/5°C and 40°C/30°C, indicating a large range of temperatures suitable for germination. Germination was limited by extremely high temperatures (45°C/35°C) and extremely low temperatures (15°C/0°C).

Dormancy can be induced in nodding thistle seeds by burial. Seeds were buried at 0-2 cm, 5 cm or 20 cm depth for three years. When tested for germination, rates were found to have percentage viabilities of 0.6%, 20.9% and 56.8% respectively (Anon 1986).

Popay & Thompson (1979) also conducted experiments investigating the effect of different depths of seed burial on the viability of nodding thistle seeds. They found that seeds at the soil surface disappeared fairly rapidly, partly because of germination. There were few viable seeds remaining on the soil surface after two years and negligible amounts at the end of three years. Seeds buried to a depth of 4-6 cm lost viability much more slowly, and after three years about 50% of the seeds buried were still viable. The largest differences were discovered when seeds were buried to 19-21 cm depth where little reduction in viability was observed over the four year period.

A longer term study by James *et al.* (1998) found that nodding thistle seed buried in the top 1-2 cm of soil declined rapidly and after 16 years there was no viable seed present. At the other two depths (5 cm and 20 cm) studied 0-20% and 1-32% respectively of the seed was still viable after 16 years. The range of values indicate differences due to soil type.

2.4.3.2. Effect of pasture competition on nodding thistle

Established continuous pasture is effective in inhibiting nodding thistle seedlings (Edmonds & Popay 1983). However, recent experiments indicate that the grass component of the sward has more of an inhibitory effect on nodding thistle than the legume component. An experiment by Nicholson *et al.* (1990) investigated the competitive relationship between nodding thistle, perennial ryegrass and white clover. They discovered that ryegrass seedlings inhibited nodding thistle seedlings when grown in a mixed sward. However, where clover plants dominated the sward, nodding thistles were large, healthy and visually unaffected. Nicholson *et al.* (1990) postulated that ryegrass is probably the component of ryegrass/clover pastures that is most responsible for inhibiting nodding thistle establishment.

Wardle *et al.* (1995) also investigated the effect of different pasture species on the emergence and establishment of nodding thistle. They discovered that nodding thistle seedling emergence was significantly higher in legume dominated swards than in grass dominated swards. In general, nodding thistle emergence was found to be strongly and negatively correlated to the total grass cover. Wardle *et al.* (1995) speculated that greater interference effects by the grasses were the reason for this result. A lower incidence of spaces for the seedlings to occupy may also have been a factor.

In the same experiment, emergence of nodding thistle in the bare ground plots was found to be highly variable. Six weeks after sowing (on 2 July 1990), emergence in the bare ground plots were an order of magnitude lower than any of the other plots. These low emergence values may have been due to a lack of protection from both grazing effects (i.e. trampling) and micro-climatic extremes. By mid-November, emergence in the bare plots was an order of magnitude higher than the other plots, indicating that protection from pasture plants was less important later in the study. This study also indicated that although emergence was often negatively affected by bare ground, once nodding thistle seedlings were established mortality was significantly reduced by the lack of competition from pasture species (Wardle *et al.* 1995).

Time necessary to initiate flowering may be doubled by competition from associated pasture plants during the seedling stage (Edmonds & Popay 1983). Edmonds & Popay (1983) investigated the survival and time to flowering of nodding thistles planted into pasture that was either sprayed beforehand with paraquat or left unsprayed. Thistles in the paraquat treatment had a significantly greater chance of survival compared to those thistles in the untreated pasture. Time to flowering was significantly less in the paraquat treatment and the majority of plants behaved as annuals, compared with the untreated pasture where most thistles acted as biennials. An experiment by Seefeldt & Armstrong (2000) found similar results with nodding thistle plants in clover only plots flowering in the first year, whereas plants in ryegrass plots were forced into at least a biennial life cycle.

In a field experiment on pasture gaps, Panetta & Wardle (1992) found that the peak emergence of nodding thistle occurred in gaps with a 10 cm diameter, when compared to 0 cm gaps, 2 cm, 6 cm and completely bare ground. However, the 10 cm emergence rate was only significantly different from the 0 cm gap treatment. Nodding thistle seedling mortality was total in the bare ground plots within five weeks of sowing the experiment; this was considered to be related to cattle trampling after rain which caused a mixing of the upper and lower soil profile. After 21 weeks the only survivors were found in the 2 cm gaps, however, after 27 weeks even these had been killed. In an associated glasshouse experiment, Panetta & Wardle (1992) found that the nature of the gap size relationship changed somewhat. The highest emergence for nodding thistle under glasshouse conditions was in the 0 cm gap and emergence generally decreased as the gap size increased.

A germination study by Phung & Popay (1981) indicated that long vegetation (6-7 cm) reduced the germination of nodding thistle seedlings by 90% when compared to bare ground. Short vegetation (2-3cm) also significantly reduced the emergence of nodding thistle though to a lesser extent. They attributed most of the differences to a large (measured) decrease in the red/far-red light ratio of soil under pasture compared to bare soil.

2.4.4. Ragwort (*Senecio jacobaea*)

Ragwort is native to Europe, Asia and Siberia (Anon. 1981). It was first reported in New Zealand near Dunedin in 1874 (Poole & Cairns 1940), and is now common throughout the country, especially in the moister areas of the North Island (Wardle 1987).

Although ragwort is generally considered to be a biennial species it is known to deviate from this behaviour by either taking more or less than two years to flower. It has even been noted to regrow from the crown after flowering and in effect become a short-lived perennial (Thompson 1985). This deviation from its biennial habit is generally associated with damage to the plant, e.g. grazing, mowing (Poole & Cairns 1940) or competition. If plants do not attain a critical size by the second year then they may adopt a perennial habit (Van der Meijden & van der Waals-Kooi 1979, Wardle 1987), and if strongly suppressed by competition may persist for many years without flowering (Harper 1958).

The ragwort plant arises from a stout root stock with numerous fleshy roots, reaching to a depth of 8cm. Rosette leaves are stalked, dark green above and paler below and the rosettes may grow to 30cm in diameter (Harper 1958). The leaf shape is pinnatifid (Poole & Cairns 1940).

Flowering stems are stout, upright and average about 75cm in height. The upper part of the stem branches extensively and supports up to 2,500 flowers (Poole & Cairns 1940). Studies at Ruakura have shown that an average plant can produce 50-150,000 achenes (seed) with a high germinative capacity. The amount of seed produced per plant is dependent, not only on size, but on locality (Poole & Cairns 1940).

The reproductive potential of ragwort is further enhanced by its ability to regrow from even small pieces of root. Under laboratory conditions portions of roots have been observed to rapidly form shoots and buds (Poole & Cairns 1940). Vegetative propagation is stimulated by disturbance, i.e. grazing damage, mowing, herbicide application etc. and can result in multiple crowns with up to 20 single flowering stems from the same plant (Wardle 1987).

Wind is probably the most important dispersal agent. Poole & Cairns (1940) found that 60% of seed produced was released from the seedhead by wind. The majority of these seeds were found within a few metres of the source plant. However, there is potential for long distance dispersal of seed if it was carried high into the air by convection currents. Other methods of dispersal potentially utilised by ragwort seed are water dispersal and dispersal through attachment to fur, wool and feathers (Poole & Cairns 1940).

Ragwort is important because of its ability to compete aggressively with forage species, reducing both quality and yield of a pasture and can amount to a significant proportion of the pasture cover (Harper 1958). It is poisonous to cattle, horses and possibly deer at all stages of its life cycle (Wardle 1987). However, sheep graze it regularly in its rosette stage without acute effect due to an ability to detoxify some of the alkaloid in the rumen (Bruere *et al.* 1990).

There is evidence that ragwort has a degree of allelopathic effect on forage plant species. Ahmed & Wardle (1993) found that the growth of perennial ryegrass, white clover, red clover, subterranean clover, and lucerne was negatively affected by the application of root and leaf leachate collected off ragwort plants. They also found that when the leachate was combined with shading from a ragwort rosette then a situation was created whereby forage plants had difficulty surviving. In a later study, Ahmed and Wardle (1994) discovered that the tissues of flowering ragwort plants were significantly more inhibitory than those from the rosette. They postulated that this could be a mechanism whereby decomposing leaves from flowering plants inhibit other pasture plants and thus create gaps in the pasture for ragwort seedlings to establish.

2.4.4.1. Germination of ragwort

Ragwort seed has no innate dormancy (van der Meijden & van der Waals-Kooi 1979, Baker-Kratz & Maguire 1984), generally has high viability and providing conditions are suitable, will germinate at any time of the year (Poole & Cairns 1940).
Experiments by van der Meijden & van der Waals-Kooi (1979) indicated that light stimulates germination and Wardle (1987) has suggested that a phytochrome system within the ragwort seed enables light quality to influence germination.

Van der Meijden & van der Waals-Kooi (1979) discovered that the timing of germination is most affected by three environmental conditions: temperature, soil moisture, and humidity. They found that the optimal conditions for ragwort germination were 15°C with 29% soil moisture content. With these conditions 92.5% germination was achieved. Over 80% germination was recorded with temperatures ranging from 10°C to 25°C. However, the highest germination was observed when temperatures fluctuated diurnally. Both Poole & Cairns (1940) and Beskow *et al.* (1994) found that ragwort had no problems germinating with winter temperatures.

Further experiments by van der Meijden & van der Waals-Kooi (1979) found that a short period of drought or frost after contact with water leads to an induced dormancy that may last for some weeks. Low humidity can also adversely affect germination in ragwort due to the drying effect this has on the top layers of soil.

Laboratory experiments by Poole & Cairns (1940) indicated that surface sown ragwort seeds with no soil or vegetation covering initially experienced retarded germination. However, after 70 days the number of seeds germinating on the surface of the soil was equivalent to that which germinated when covered by soil only. When ragwort seed was buried to a depth of 2.5 cm then no germination was recorded whatsoever. The findings of Beskow *et al.* (1994) also indicate that burial of ragwort promotes dormancy. They found that seed buried under more than 4 mm of soil was capable of a lengthy dormancy.

2.4.4.2. Effect of pasture competition on ragwort

Ragwort is essentially a pioneer species and therefore the most important factor influencing seedling survival is probably the amount of competition which it experiences from surrounding species (Harper 1958).

Vegetative cover has been shown to decrease the ability of ragwort to germinate and successfully establish in pasture (Poole & Cairns 1940, Van der Meijden & van der Waals-Kooi 1979, Phung & Popay 1981). The increased germination of ragwort seeds with reduced pasture cover has been linked to an increase in light intensity, along with an increase in the red/far red ratio received by the seeds (Beskow *et al.* 1994). Therefore, the likelihood of pasture invasion by ragwort can be lessened by maintaining an actively growing, continuous sward (Hexter 1950, Phung & Popay 1981).

Beskow *et al.* (1994) compared three types of pasture disturbance (grazing, treading and cover removal) and found that undisturbed pasture had the lowest rate of germination and establishment of ragwort seedlings. The removal of pasture cover caused the greatest increase in germination and establishment whereas grazing and treading also caused an increase though to a lesser extent.

In an early experiment investigating ragwort emergence under different grazing management, Cameron (1935) reported that ragwort sown at a density of 100 seeds per square foot produced no established seedlings on short continuous turf, 86,120 seedlings/acre on overgrazed pasture and 2,308,680 seedlings/acre on bare soil. This experiment again emphasises the importance of a dense sward to reduce ragwort establishment.

The height of the pasture cover can influence the germination of ragwort seeds. Phung & Popay (1981) found that ragwort germination was greatest with no pasture cover and decreased significantly with either short (2-3cm) or long vegetation (6-7cm).

Harper & Wood (1957) reported that white clover and perennial ryegrass sown at the same time as ragwort seed reduced emergence and depressed establishment of ragwort. They postulated that clover could be the most important competitor for ragwort seedlings due to the similar growth form of clover and ragwort seedlings. However, Seefeldt & Armstrong (2000) found that ragwort seeds sown at the same time as ryegrass and white clover had no effect on weed emergence but did affect the eventual weed biomass present in the plot.

Sheep are often used to control ragwort infestations and are effective at preventing plants from flowering and setting seed. However, although grazing kills some plants, many persist as small rosettes giving a superficial impression of elimination (Poole & Cairns 1940).

CHAPTER THREE

Effect of Varying Sowing Rates of Perennial Ryegrass on Weed Invasion in Established Pasture - a Tray Experiment.

3.1. Introduction

The aim of this experiment was to determine whether there is any ongoing advantage, with respect to reducing weed invasion, in high sowing rates of perennial ryegrass once the pasture has established. To this end a tray experiment was established with different seeding rates of perennial ryegrass. Eight months after the pasture was established weed seeds were introduced into the trays and weed emergence, size and mortality were assessed in the different treatments.

The tray experiment had two objectives. The first was to investigate whether the original sowing rates of perennial ryegrass and white clover had any influence on the resulting weed population i.e. emergence, the timing of emergence, weed size and mortality. The second objective was to investigate whether the ryegrass tiller density at the time of sowing of the weed seeds had any effect on the same variables. Treatment 1 was not included in the second objective as it not a logical part of the progression of increasing ryegrass densities.

Although tray experiments create by their controlled nature an artificial situation, the results can be useful to help understand the mechanisms involved in the field.

3.2. Materials and methods

3.2.1. Establishment of pasture swards in trays

On 7 September 1999 polystyrene trays measuring 540 x 340 x 80 mm deep were filled with Horotiu silt loam soil (organic C 6.2%, sand 58%, clay 15%, silt 27%). Perennial ryegrass (cv. Bronsyn) was hand sown into these trays at rates of 0, 5, 10, 20, 40, 80, 160 or 320 kg seed/ha. All trays (including 0) were also sown with 5 kg/ha of white clover seed (50:50 mix of cv. Sustain and Aran). In addition there was an unsown treatment which had neither ryegrass nor white clover sown into it (Table 3.1). There were 136 trays in total in the experiment. The number of trays in each treatment is indicated in Table 3.1.

Table 3.1. The seeding rates of perennial ryegrass and white clover sown in trays on 7 September 1999 (8 months prior to sowing weed seeds) and the number of trays relating to each treatment.

Treatment	Ryegrass sowing rate (kg/ha)	White clover sowing rate (kg/ha)	Number of trays
1	0	0	16
2	0	5	12
3	5	5	15
4	10	5	14
5	20	5	16
6	40	5	15
7	80	5	16
8	160	5	16
9	320	5	16

The trays were watered as required and fertilised weekly with Long Ashton nutrient solution (Hewitt 1966). The swards were trimmed monthly to a height of 30 mm using electric hand shears and the trimmings were removed from the trays. Throughout the duration of the experiment all volunteer weeds were removed. Slug bait (Mesurol, active ingredient 20 g/kg methiocarb, at 10 kg/ha) was applied at monthly intervals. After 50 days in the glasshouse the trays were placed outside on low benches.

3.2.2. Weed seed germination tests

Germination tests were conducted in both the laboratory and in the field. For the laboratory tests, 30 seeds of each weed species were placed on moistened filter paper in a Petri dish. The dishes were then placed in a 20°C incubator and germination was monitored over a period of six weeks.

Field germination tests were also conducted to investigate likely seedling emergence under a vegetation canopy, to allow realistic planning of seed numbers to use in the experiments. Five hundred seeds of each weed species were sown into marked quadrats in an established pasture. The pasture was watered so that moisture would not limit germination and germination was monitored over 22 days.

Table 3.2: Percentage germination of weed seeds in laboratory and field germination tests.

	Petri dish	Field
Scotch thistle	16.7 %	21.4 %
Nodding thistle	16.7 %	6.2 %
Ragwort	0 %	10.8 %
Hedge mustard	70.0 %	0.6 %

Due to the low germination percentages gained in these tests (Table 3.2) it was decided that 500 seeds of nodding thistle and ragwort would be sown in the experiment. Although hedge mustard had high germination in the Petri dish, most germination in the experiments would occur under vegetation and so 500 seeds of this species were used. When 500 Scotch thistle seeds were sown in the field germination tests, 107 seedlings emerged. This was considered an excessive number of seedlings to map in the experiment and therefore only 250 Scotch thistle seeds were sown in the field experiment. However, due to high early germination in the field experiment (which was sown 4 weeks earlier than the tray experiment) only 125 Scotch thistle seeds per tray were sown in the tray experiment.

All of the weed seeds used in the experiments were collected from sites around the Waikato in the summer of 1999-2000, and stored in air-tight containers until required.

3.2.3. Introduction of weed seeds

Perennial ryegrass tillers and white clover growing points were counted on 18 May 2000 in a 50 mm x 200 mm quadrat in each tray to estimate pasture composition. In the same week, weed seeds were evenly scattered onto the soil surface in the centre of each tray, leaving an unsown 60 mm buffer around the outside of each tray. Each tray had only one weed species sown into it. The species were nodding thistle (500 seeds), Scotch thistle (125 seeds), hedge mustard (500 seeds) and ragwort (500 seeds). The original intention was to have four replications of each species at each treatment; however, at the time of sowing the weed seeds for this experiment some trays were unavailable due to demands from other experiments (see Table 3.3).

Table 3.3. The number of trays present in each treatment for the four weed species (see Table 3.1. for explanation of treatments).

Treatment	Scotch thistle	Ragwort	Hedge mustard	Nodding thistle
1 (0/0)	4	4	4	4
2 (0/5)	3	3	3	3
3 (5/5)	3	4	4	4
4 (10/5)	3	4	4	3
5 (20/5)	4	4	4	4
6 (40/5)	3	4	4	4
7 (80/5)	4	4	4	4
8 (160/5)	4	4	4	4
9 (320/5)	4	4	4	4

At monthly intervals, immediately after trimming, all emerged weed seedlings were mapped to enable the fate of individual weed seedlings to be followed. Mapping was carried out using a sheet of acetate on a piece of glass that was positioned above the tray. The position of each weed seedling in the tray was marked onto the sheet of acetate. The same sheet of acetate was used at each count for that tray, but a different coloured pen was used each time so that the fate of existing seedlings could be checked and newly emerging seedlings identified as such. Scotch thistle seedlings were counted and removed on 31 August 2000. At this point the size of the Scotch thistle seedlings made them prone to damage during the artificial grazing in the low ryegrass density trays. Ragwort, hedge mustard and nodding thistle seedlings were counted and removed on 5 October 2000, for similar reasons to that of Scotch thistle. All harvested weed seedlings were dried and a dry weight determined.

3.3. Results

3.3.1. Pasture condition when weed seeds sown

The trays in this experiment were continually weeded to remove broad-leaved weeds and volunteer grasses. Therefore the only two species present in the trays when the weed seeds of interest were sown were perennial ryegrass and white clover. It is especially important to note that in the tray experiment, Treatment 1 was not sown with any pasture species (Table 3.1) and therefore was bare soil. Due to the lack of pasture species present, Treatment 1 was excluded from the analysis of pasture condition at sowing for the tray experiment.

There was still a strong relationship between sowing rate and ryegrass tiller density eight months after the pasture species were sown (Fig. 3.1). However, no curve was fitted to this data due to uncertainty as to where to place the line due to the discontinuity between the number of ryegrass tillers present at the 0kg/ha ryegrass sowing rate and the number of ryegrass tillers present at the 5kg/ha sowing rate.

When the treatments sown with ryegrass were analysed separately (i.e. Treatments 3-9), a significant ($P<0.001$) exponential model was fitted to the data, which accounted for 66.4% of the variation in the data. The curve appears to be going asymptotic.

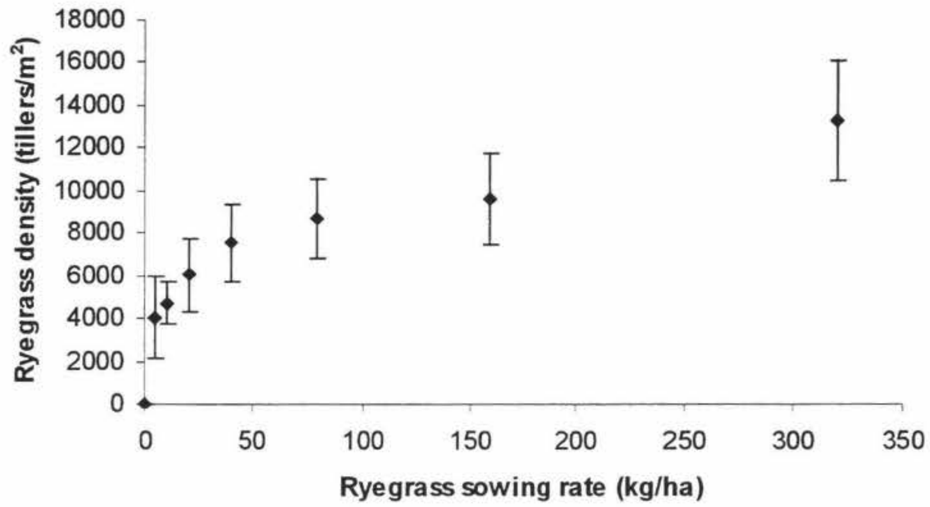

Figure 3.1. Effect of perennial ryegrass sowing rate on ryegrass tiller density (8 months after sowing) in tray experiment (error bars indicate standard deviation).

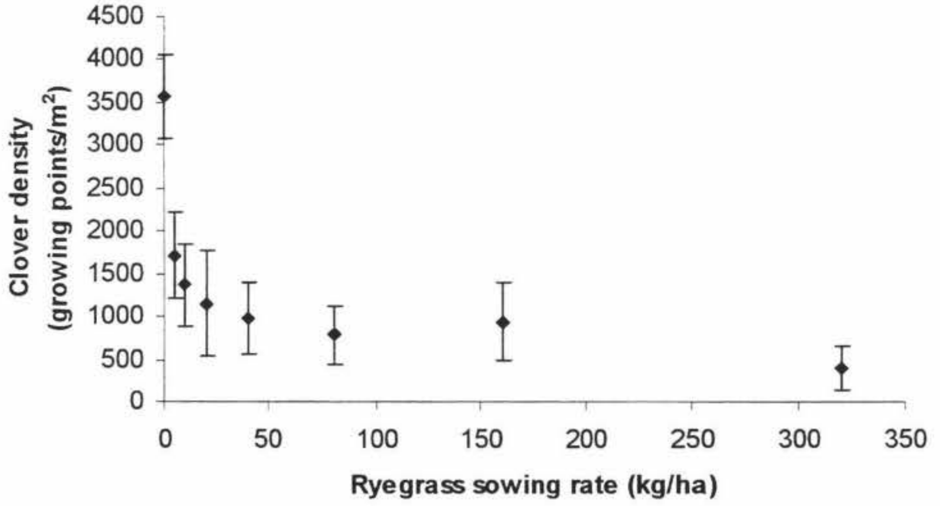

Figure 3.2. Effect of ryegrass sowing rate on the density of white clover growing points (8 months after sowing), in the tray experiment (error bars indicate standard deviation).

Eight months after the pasture species were sown the number of white clover growing points present in the trays decreased as the ryegrass sowing rate increased (Fig 3.2). The amount of clover present dropped off sharply with the introduction of ryegrass (i.e. at 5kg/ha ryegrass) and then only gradually declined as the ryegrass sowing rate increased.

This was a significant exponential relationship (P<0.001), accounting for 73.2% of the variation in the data.

There was a general trend for the number of white clover growing points in the trays to decrease as the number of ryegrass tillers increased (Fig. 3.3). After a square root transformation was performed on the ryegrass tillers, an exponential decay curve could be fitted which accounted for 74.6% of the variability of the data. This trend was highly significant (P<0.001).

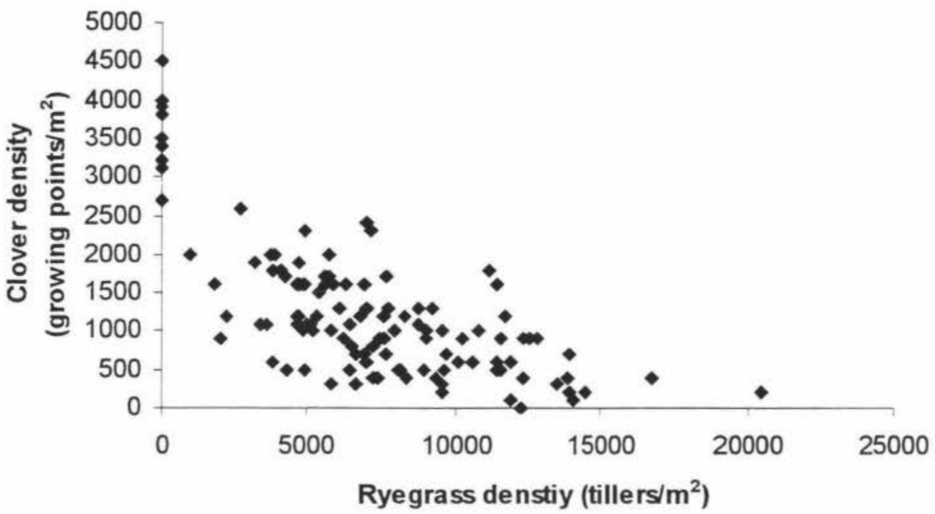

Figure 3.3. Effect of ryegrass tiller density on white clover growing points (8 months after sowing), in the tray experiment.

3.3.2. Climate data for trial

The weather data presented in this section covers the period of both this experiment (18 May to 5 Oct) and the field experiment (presented in Chapter 4). The data was collected at the Ruakura Research Centre weather station which is situated 700m from the tray experiment and 900m from the field experiment.

3.3.2.1. Air temperature

The maximum air temperatures for this period are presented in Figure 3.4. Apart from a cold period in the middle of June the temperatures throughout the experiment seem reasonably constant. It is important to remember that these are maximum values only and that these temperatures would not have been maintained throughout the day. The average maximum air temperature throughout the duration of the tray experiment was 14.9 °C and for the field experiment was 16.2 °C.

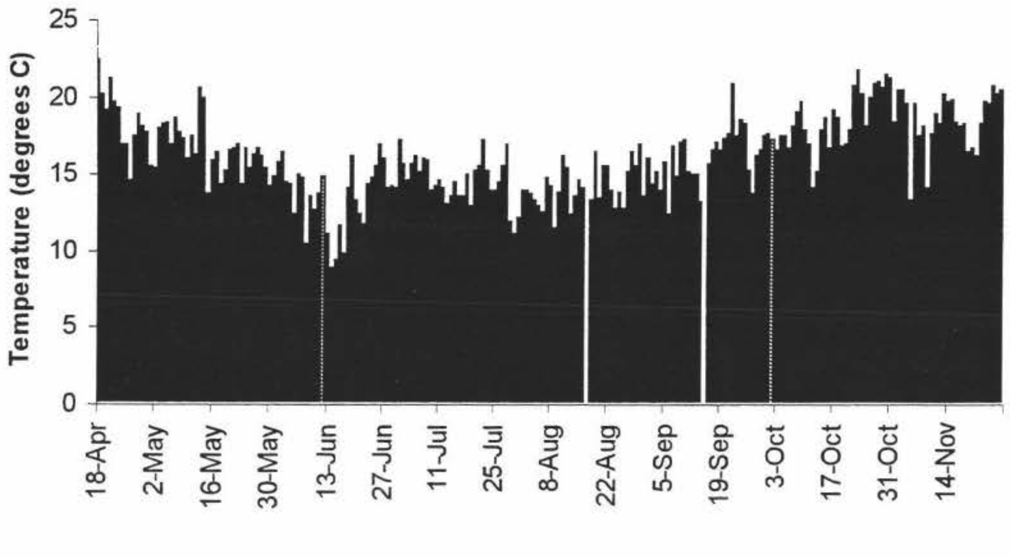

Figure 3.4. Daily air (screen) maximum temperatures for the Ruakura Research Centre, in 2000 (values missing for 17 August and 15 September), throughout the duration of the experiments.

The minimum daily air temperatures are presented in Figure 3.5. The average reading for the tray experiment was 5.2 °C and for the field experiment was 6.3 °C.

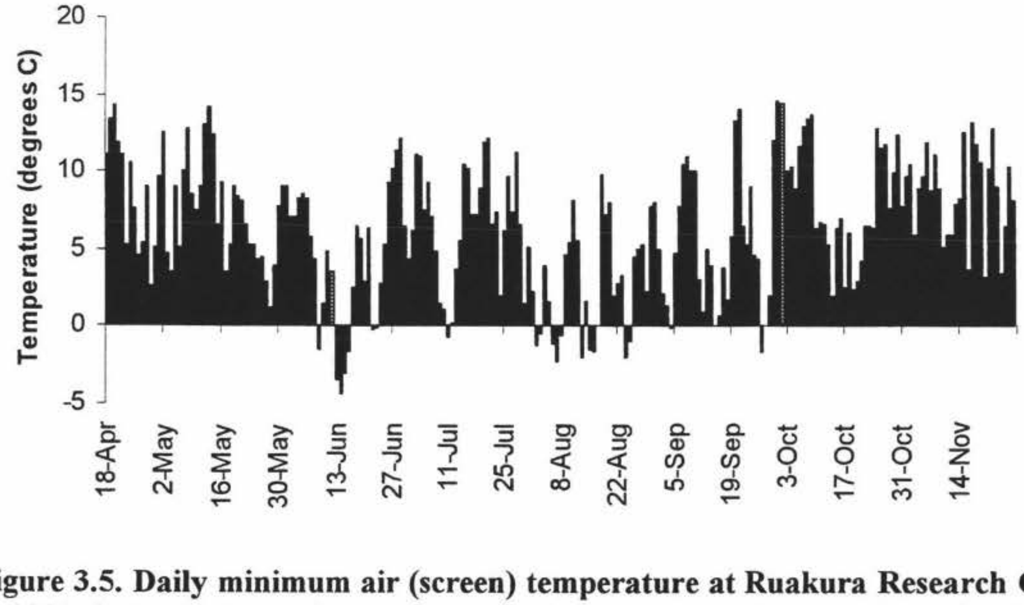

Figure 3.5. Daily minimum air (screen) temperature at Ruakura Research Centre, in 2000, (values missing for 17 August and 15 September), throughout the duration of the experiments.

3.3.2.2. Grass temperature

The minimum grass temperatures experienced by the Ruakura Research Centre during the period after the weed seeds were sown are presented in Figure 3.6. The interesting points to note are the series of frosts soon after the weed seeds in the field were sown (i.e. between 23 April and 29 April). There was another series of frosts soon after the tray experiment was sown (i.e. between 24 May and 29 May). Also of interest is the period of severe frosts experienced from 8 June to 16 June when the minimum grass temperatures were below 1 °C throughout this period. During this same period three frosts were experienced that were less than –5.5 °C.

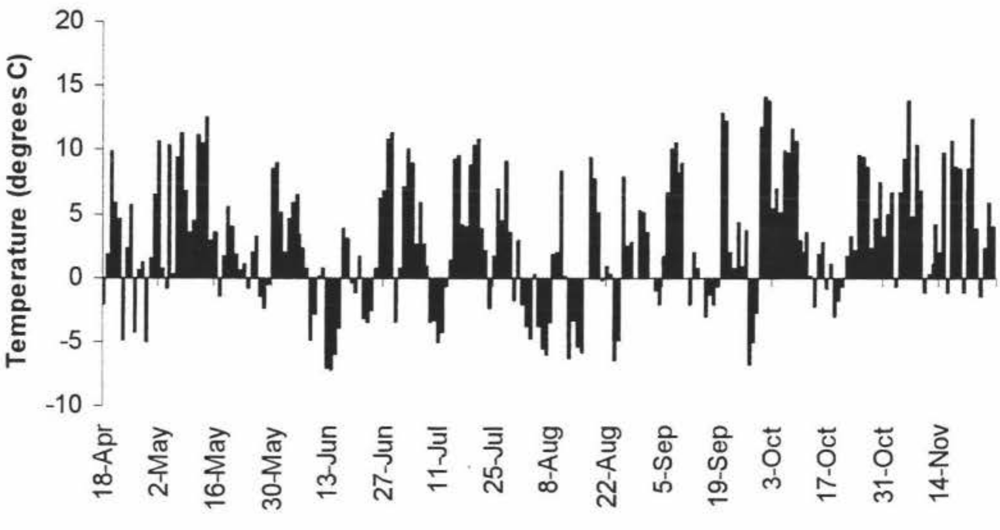

Figure 3.6. Daily minimum grass temperature at Ruakura Research Centre, in 2000, (values missing for 17 August and 15 September), throughout the duration of the experiments.

3.3.2.3. Rainfall

The monthly rainfall data is presented in Figure 3.7. It is apparent from these data that moisture would not have been a limiting factor with respect to plant growth.

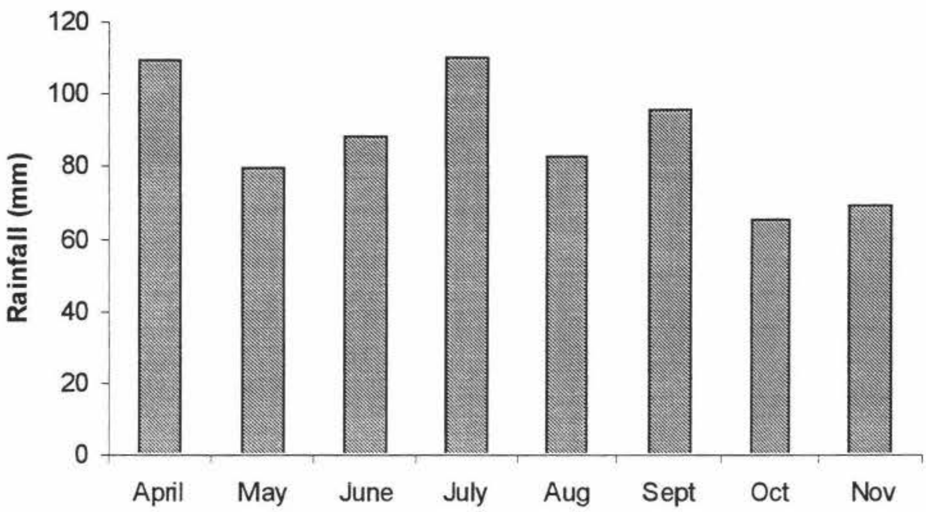

Figure 3.7. Total monthly rainfall for the Ruakura Research Centre, in 2000, for the duration of the experiments.

3.3.3. Weed results

3.3.3.1. Weed emergence

This section relates to the total number of sown weed seedlings that emerged throughout the tray experiment. It does not take into account whether the seedlings survived or died. Mortality will be dealt with in a later section (Section 3.3.3.4).

For the following section, all of the weed emergence data underwent a square root transformation prior to an analysis of variance. For the regression analyses the emergence data did not require transformations unless otherwise stated.

Scotch thistle – The highest Scotch thistle germination was 65 seedlings out of the 125 seeds sown (52% germination). This occurred in Treatment 2 (0/5). This value is much higher than the original germination test results (Table 3.2).

Very low Scotch thistle seedling emergence was observed in Treatment 1 (0 kg/ha ryegrass and 0 kg/ha clover seed, hereafter abbreviated to 0/0) compared with the treatments sown with pasture plants (Fig 3.8). Of the 125 seeds sown per tray, the average emergence for Treatment 1 was 2.5 seedlings per tray compared with 40.5 in the other treatments. An analysis of variance indicated a highly significant difference ($P<0.001$) between Treatment 1 and all other treatments.

There appeared to be a trend for Scotch thistle emergence to decrease as the ryegrass sowing rate increased (Fig. 3.8). This was investigated with an analysis of variance, however, even with Treatment 1 (0/0) removed this trend was not significant ($P>0.05$). It was not necessary to transform the data for the analysis of variance once Treatment 1 was removed, as the data then had homogenous variance.

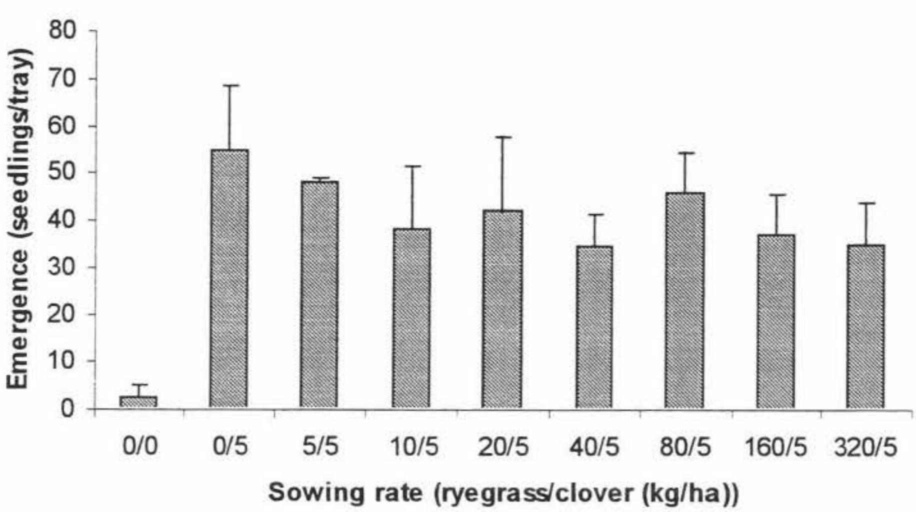

Figure 3.8. Effect of pasture sowing rates on mean Scotch thistle emergence (over 14 weeks) in trays from the 125 sown seeds (error bars indicate standard deviation).

A linear regression was performed comparing Scotch thistle emergence with ryegrass tiller counts. A significant ($p<0.05$) linear decline was observed (Fig. 3.9), which accounted for 13.2% of the variation in the data. However, when the ryegrass-only plots (Treatment 3-9) were analysed separately, no significant regression was found.

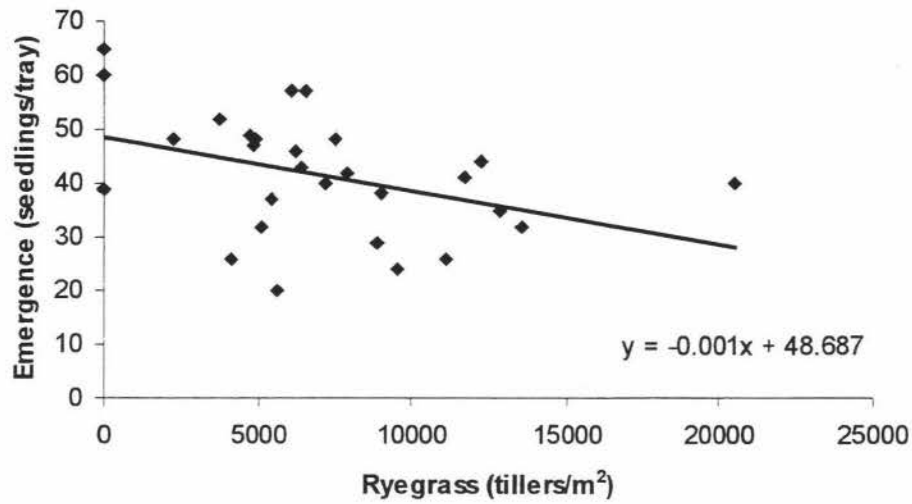

Figure 3.9. The relationship between Scotch thistle emergence per tray (over 14 weeks) and ryegrass tiller density.

Ragwort – The highest emergence value in the tray experiment was 216 seedlings out of the 500 seeds sown (43% germination). As with the Scotch thistle results, this value is much higher than the germination tests indicated (Table 3.2).

An analysis of variance indicated that there were no significant differences in ragwort emergence between the different sowing rates (Fig. 3.10). However, if Treatment 1 (0/0) is removed then the subsequent analysis of variance indicates that there were significant ($P<0.05$) differences in ragwort emergence between the sowing rates. A significant ($P<0.01$) and positive linear trend for ragwort emergence to increase as sowing rate increases was also apparent once Treatment 1 was removed (Fig. 3.10).

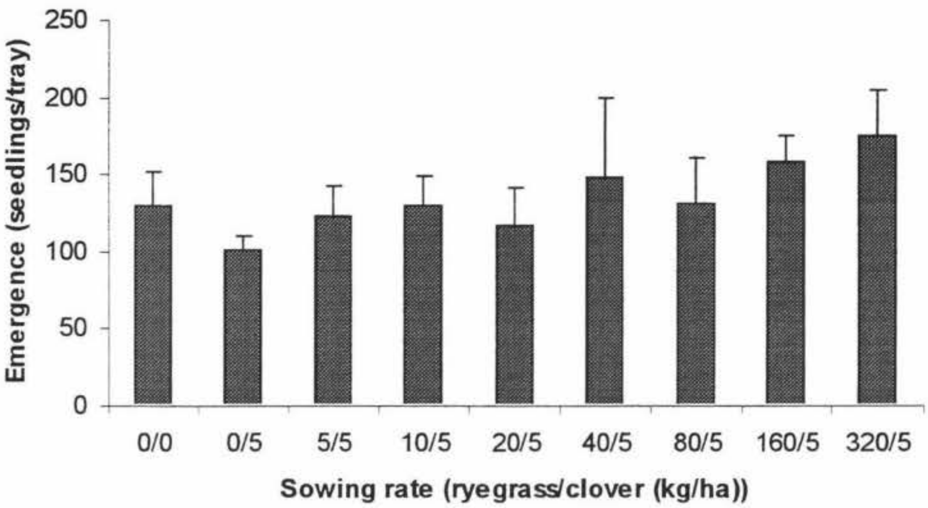

Figure 3.10. Effect of pasture sowing rates on mean ragwort emergence in trays (over 20 weeks) from the 500 sown seeds (error bars indicate standard deviation).

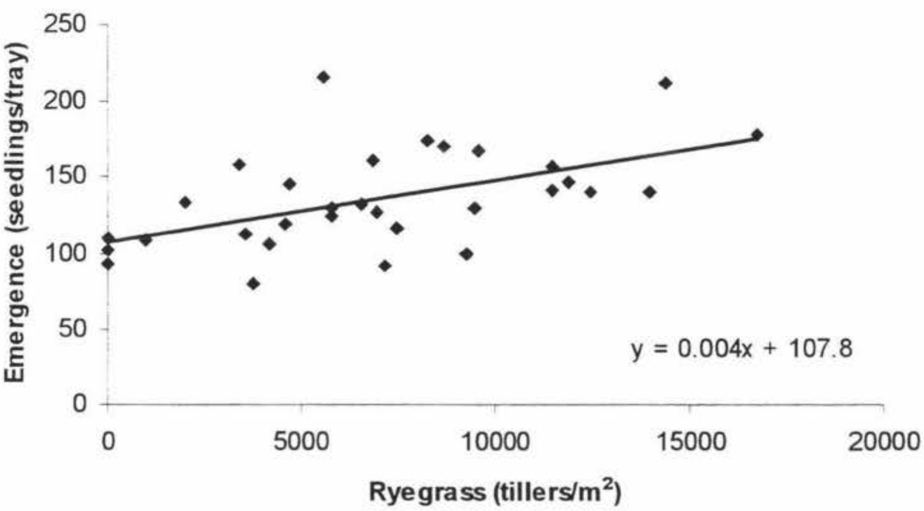

Figure 3.11. The relationship between ragwort emergence per tray (over 20 weeks) and ryegrass tiller density.

The linear regression between ragwort emergence and ryegrass tiller density was significant ($P<0.01$) although it accounted for only 26.5% of the variation in the data (Fig. 3.11). This indicates that as ryegrass tiller density increases, the number of ragwort seedlings emerging also increases. With the clover only (0/5) treatment removed, the trend was still significant (p<0.05), although the line accounts for only 16.9% of the variability in the data.

Hedge mustard – The number of hedge mustard seedlings emerging in the trays was very low (Fig. 3.12). The highest emergence was in Treatment 1 (0/0) where the mean emergence was 31.75 seedlings per tray. However, even this amounted to only 6.4% of the seeds sown emerging as seedlings. The other treatments all had mean emergence values of less than five seedlings per tray (or 1% emergence). This value is similar to that found in the field germination tests, however much lower than the germination rate of 70% recorded in the laboratory germination test (Table 3.2).

The analysis of variance indicated that hedge mustard emergence in Treatment 1 (0/0) was significantly (p<0.001) higher (Fig. 3.12) than in treatments with pasture species present. If Treatment 1 was removed then the analysis of variance showed no differences between the numbers of hedge mustard seedlings emerging at any sowing rate.

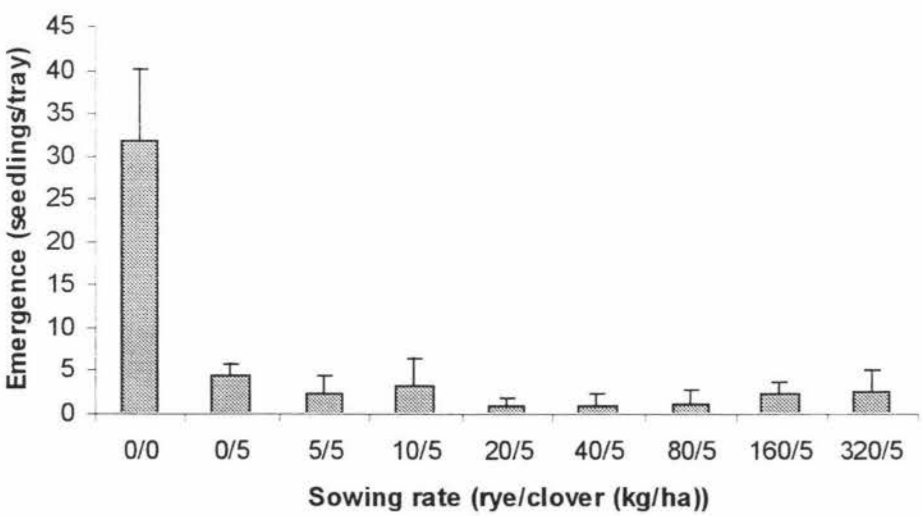

Figure 3.12. Effect of pasture sowing rates on mean hedge mustard emergence (over 20 weeks) in trays from the 500 sown seeds (error bars indicate standard deviation).

No significant relationship was found between the ryegrass tiller density and the number of hedge mustard seedlings emerging in the plots (Fig. 3.13).

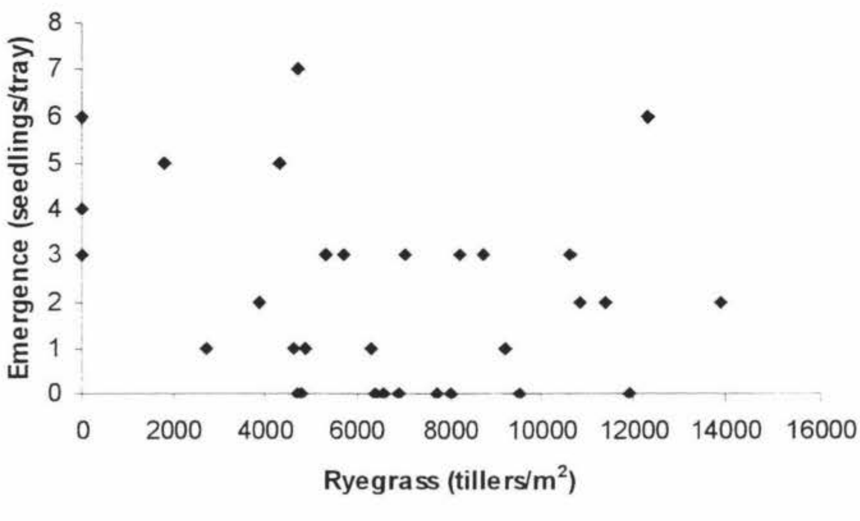

Figure 3.13. The relationship between hedge mustard emergence per tray (over 20 weeks) and ryegrass tiller density.

Nodding thistle – The highest nodding thistle emergence occurred in Treatment 3 (5/5) where 22 seedlings emerged out of the 500 seeds sown (4.4%). Unlike both Scotch thistle and ragwort, this species had lower germination in the tray experiment than was observed in the germination tests (Table 3.2).

There was no nodding thistle emergence in Treatment 1 (0/0) of the tray experiment (Fig. 3.14). When an analysis of variance was performed, without Treatment 1, it indicated that there were no significant differences or trends between the different ryegrass sowing rates. However, if an outlier (sowing rate 5/5, 22 seedlings) was removed from the analysis then a significant positive trend ($P<0.05$) became apparent for nodding thistle emergence to increase as ryegrass sowing rate increases.

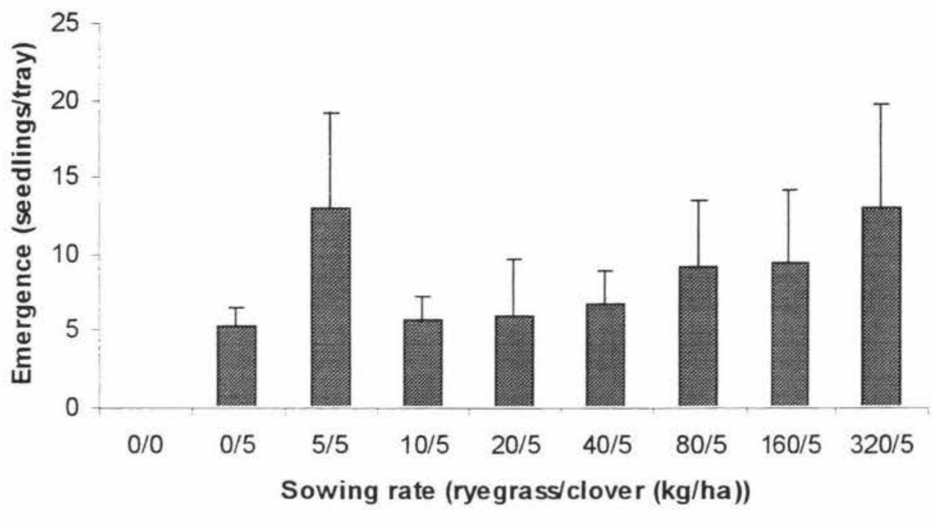

Figure 3.14. Effect of pasture sowing rates on mean nodding thistle emergence in trays (over 20 weeks) from the 500 sown seeds (error bars indicate standard deviation).

The regression analysis of ryegrass tiller density and nodding thistle emergence indicated that there was no significant relationship between these two variables. However, when an outlier (22 seedlings, 3200 tillers) was removed then a positive linear correlation ($P<0.05$) was found between ryegrass tillers and the number of nodding thistle seedlings that emerged (Fig. 3.15). The variance that was accounted for by this relationship was only 14.8% though. For both of these analyses the nodding thistle emergence data underwent a square root transformation.

When the treatments sown with ryegrass (i.e. Treatments 3-9) were analysed separately there were no significant trends in the data. Even with the same outlier removed there was still no correlation. Again the emergence data underwent a square root transformation.

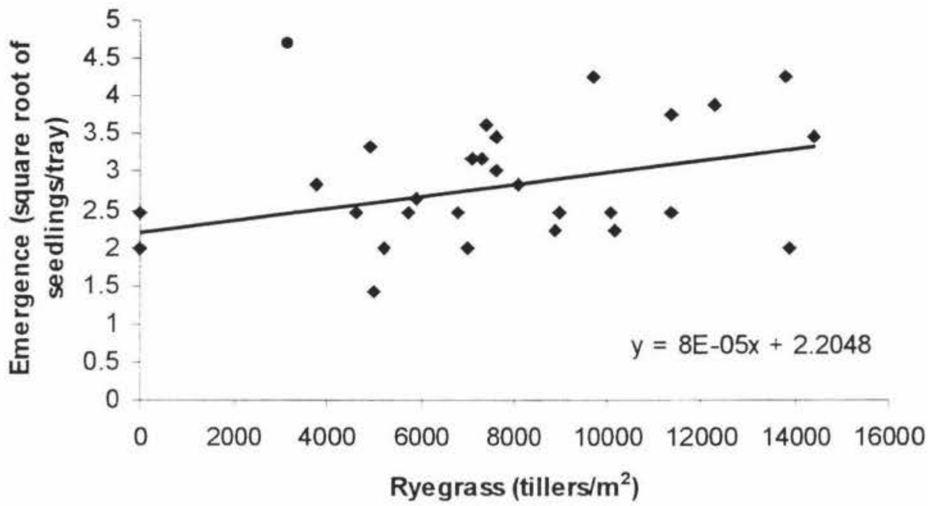

Figure 3.15. The relationship between nodding thistle emergence per tray (over 20 weeks) and ryegrass tiller density (outlier marked with "•"). The trend line is drawn without the influence of the outlier.

3.3.3.2. Weight of weeds

Scotch thistle - The Scotch thistle seedlings remaining at the end of the experiment in Treatment 1 (0/0) weighed significantly less ($P<0.001$) than those in Treatment 2 (0/5) (Fig. 3.16). However, the seedlings harvested from Treatment 1 and Treatment 2 were significantly ($P<0.001$) heavier than the seedlings harvested from the ryegrass treatments. With Treatment 1 (0/0) removed, the analysis of variance also confirmed that there was a significant ($P<0.05$) general decline in the mean weight per plant as ryegrass sowing rate increased.

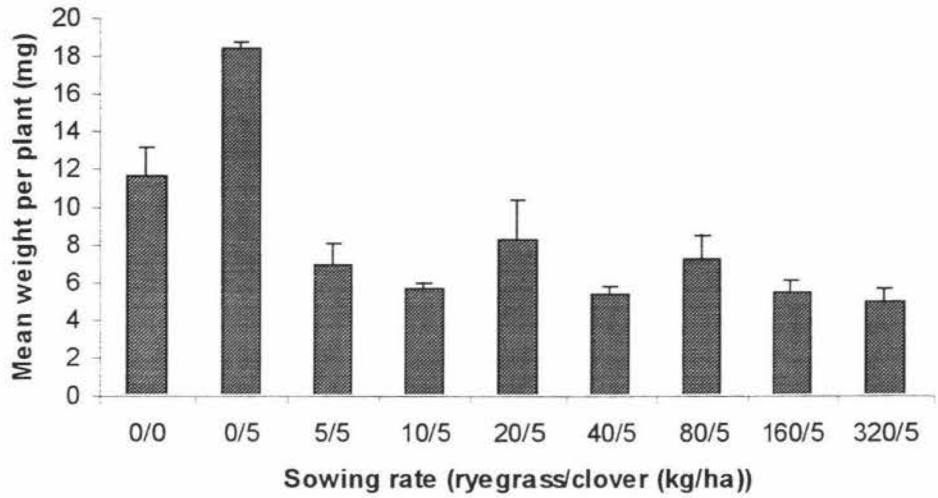

Figure 3.16. Mean dry weight of Scotch thistle seedlings at each sowing rate, 14 weeks after sowing (error bars indicate standard deviation).

After graphing plant weight against ryegrass tiller density (Fig. 3.17) it was not feasible to fit a trend line through the data points. There are numerical fitting problems due to the nature of the data, i.e. there was a large gap between zero ryegrass tillers and the rest of the data and therefore too much uncertainty existed as to where to place the line.

When the treatments originally sown with ryegrass (i.e. Treatments 3-9) were analysed separately, a general decline in mean weight of Scotch thistle plants could be seen as ryegrass tiller density increased. The decline although significant ($p<0.05$, $r^2=0.134$), was strongly influenced by one data point (20,500 tillers, 4.1mg). With this point removed, the linear regression was not significant.

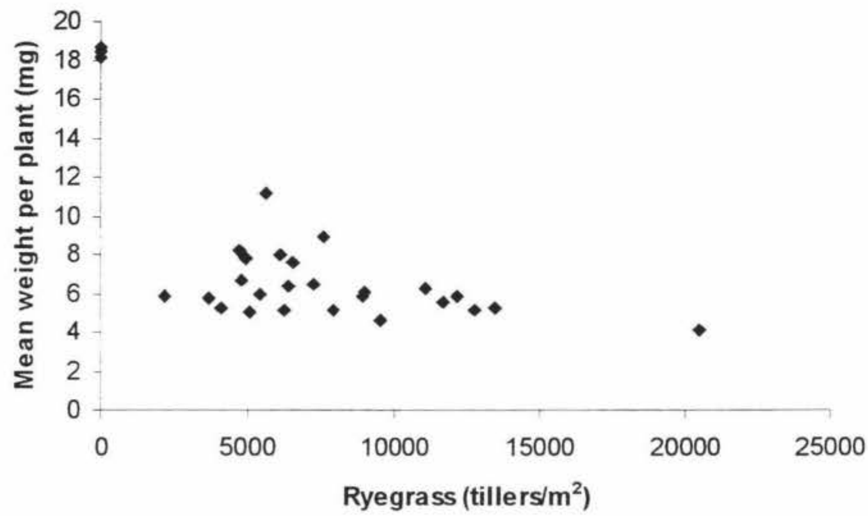

Figure 3.17. The relationship between the size of Scotch thistle seedlings, 14 weeks after sowing, and perennial ryegrass tiller density within the trays.

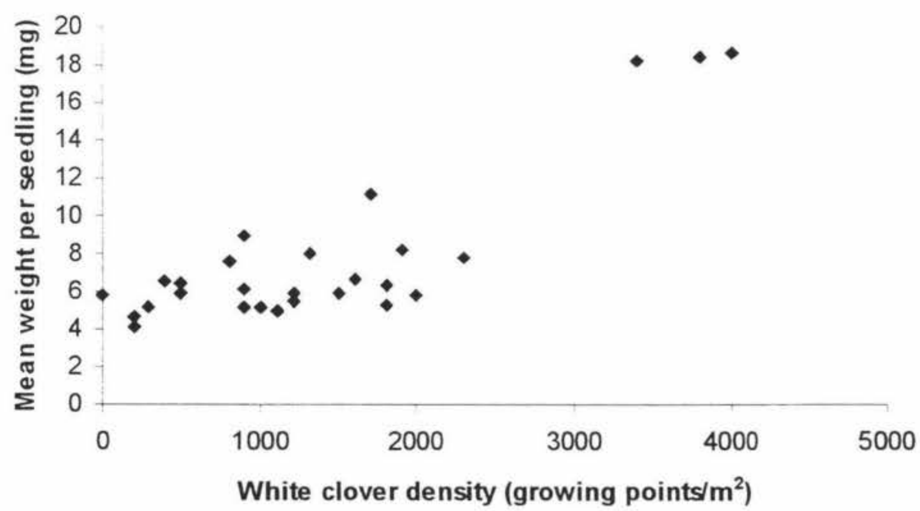

Figure 3.18. The relationship between the size of Scotch thistle plants, 14 weeks after sowing, and white clover density within the trays.

The amount of white clover present in the trays appeared to have a significant positive effect ($P<0.001$) on the weight of the individual Scotch thistle seedlings (Fig. 3.18). However, a trend line was not fitted to this data either, due to problems ascertaining where the line would fit due to the large gap between the 2,500 white clover growing points and 3,500 growing points (Fig. 3.18). Once the data points relating to Treatment

2 (0/5) were removed from the analysis to overcome the problem of the large gap in the graph, a significant ($P<0.05$, $r^2=0.142$) linear regression was obtained.

Ragwort - The analysis of variance indicated that the ragwort seedlings in Treatments 1 (0/0) and 2 (0/5) were significantly heavier than those in the treatments sown with ryegrass ($P<0.01$) (Fig. 3.19). With both Treatments 1 and 2 removed, an analysis of variance indicated that there were no significant trends for the weight of ragwort seedlings to either increase or decrease with an increase in ryegrass sowing rate.

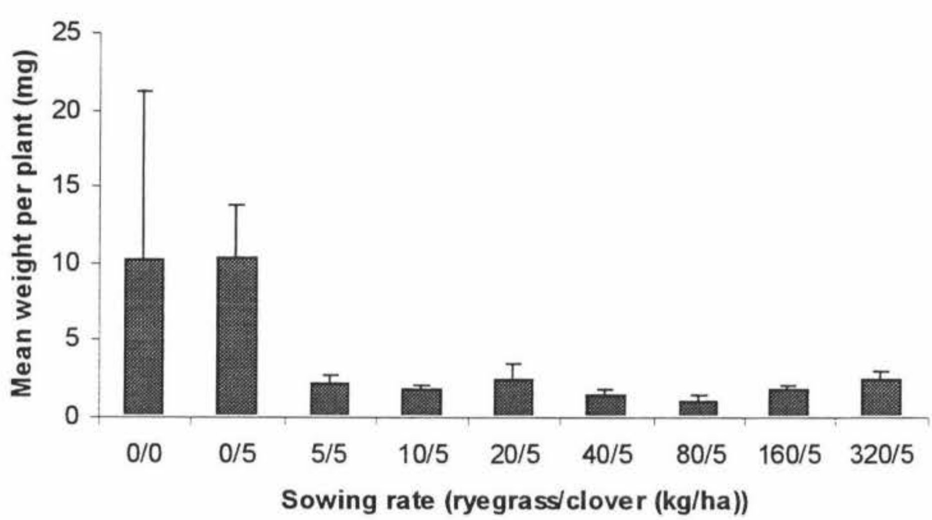

Figure 3.19. Mean dry weight of ragwort seedlings at each sowing rate, 20 weeks after sowing (error bars indicate standard deviation).

A trend line was not fitted to the data due to problems knowing where the turning point was, however it was apparent from the graph that ragwort seedlings were much larger in the plots that contain no ryegrass (Fig. 3.20). There were no significant differences between weights of ragwort plants with the treatments sown with ryegrass.

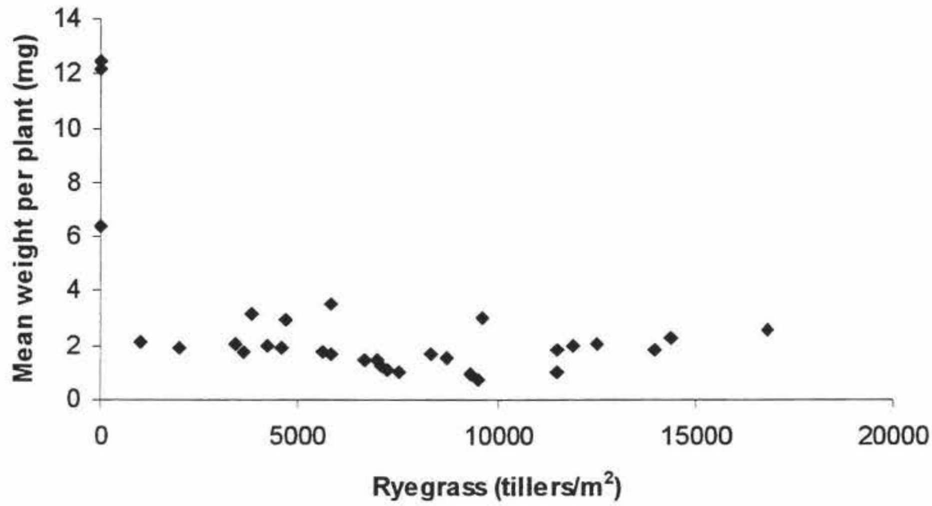

Figure 3.20. The relationship between the size of ragwort seedlings, 20 weeks after sowing, and perennial ryegrass tiller density within the trays.

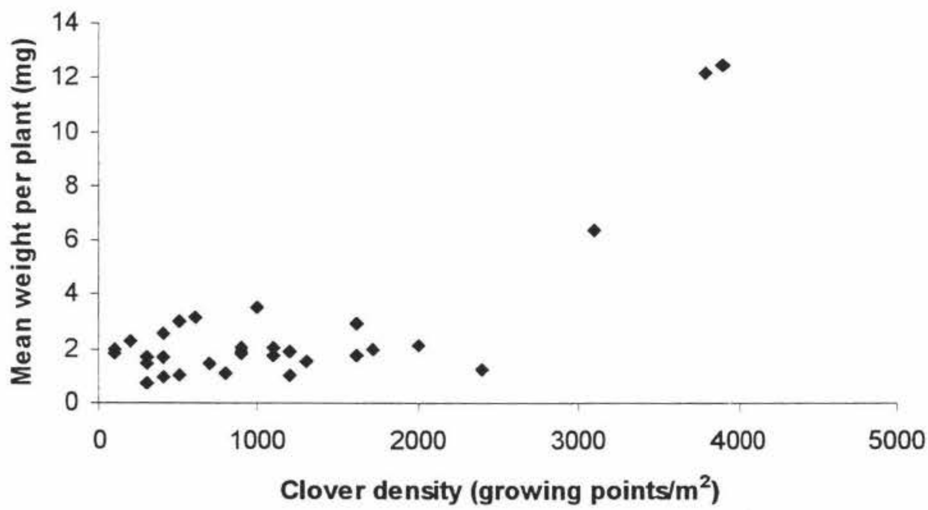

Figure 3.21. The relationship between the size of ragwort seedlings, 20 weeks after sowing and white clover density within the trays.

The mean weight of the ragwort plants was graphed against clover density (Fig. 3.21). It is apparent from this graph that ragwort growing in trays with a high density of clover tended to grow larger than those plants growing in trays that had a lower density of clover. A trend line was not fitted to this data, again due to problems ascertaining where the line would go due to the discontinuities at high densities of clover.

Hedge mustard - Due to low emergence values in the tray experiment some trays had no hedge mustard seedlings whatsoever. Trays with no emergence were necessarily removed from the analysis of weight per plant.

An analysis of variance indicated that hedge mustard plants harvested from Treatment 1 (0/0) were significantly ($P<0.001$) larger than those harvested from the other treatments (Fig. 3.22). Hedge mustard plants growing in Treatment 2 (0/5) were significantly ($P<0.01$) larger than those plants harvested from the treatments that were sown with ryegrass. For the above analyses the plant weight data underwent a log transformation to achieve homogeneous variance amongst the treatments.

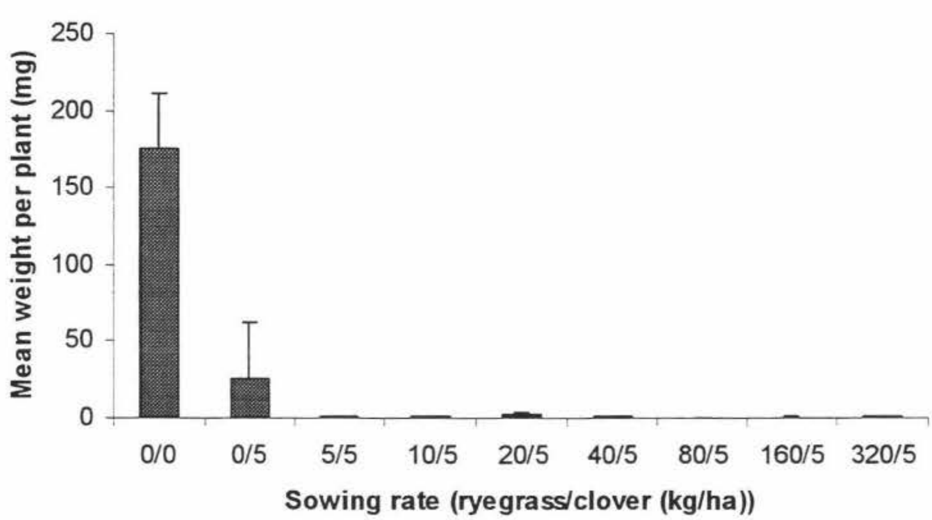

Figure 3.22. Mean dry weight of hedge mustard seedlings at each sowing rate, 20 weeks after sowing (error bars indicate standard deviation).

A significant ($P<0.01$) negative relationship was found between ryegrass tiller density and the log transformed mean plant weight data (Fig. 3.23). However, when the treatments sown with ryegrass were analysed separately there was no significant relationship.

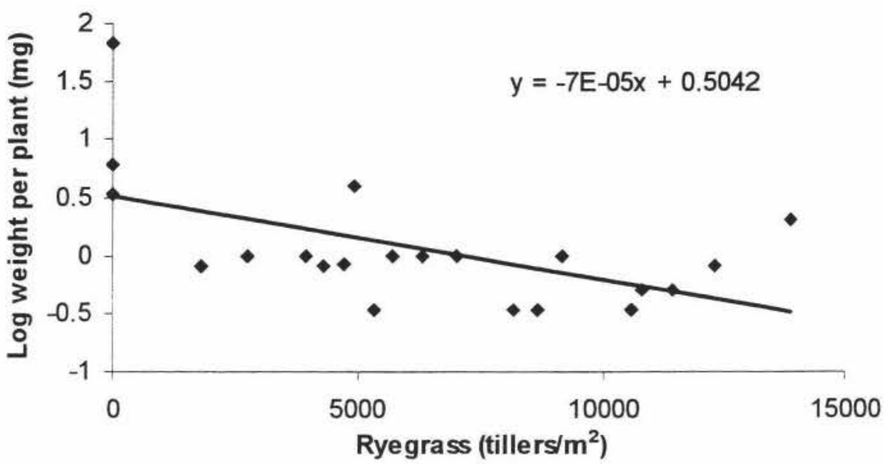

Figure 3.23. The relationship between the size of hedge mustard seedlings (log transformed), 20 weeks after sowing and ryegrass density within the trays.

Nodding thistle - As there was no nodding thistle emergence in Treatment 1 (0/0) this treatment was not included in the plant weight analysis.

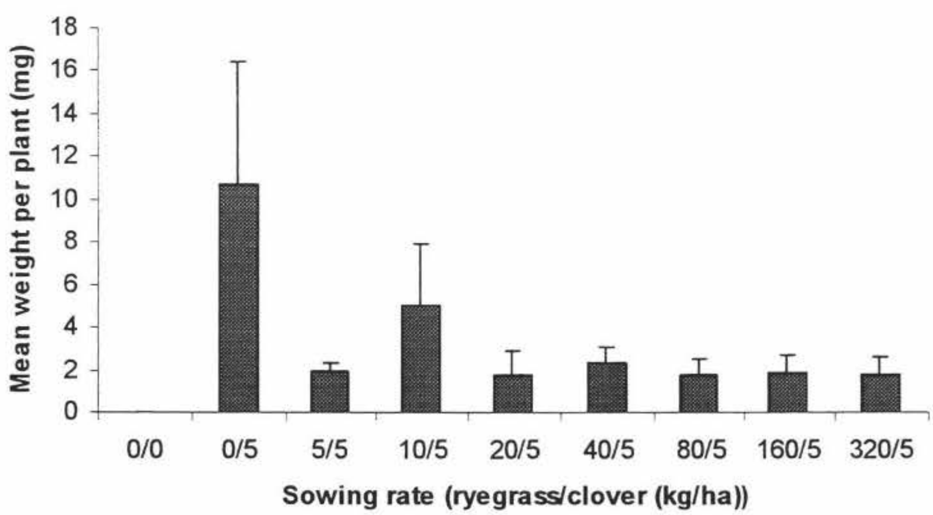

Figure 3.24. Mean dry weight of nodding thistle seedlings at each sowing rate, 20 weeks after sowing (error bars indicate standard deviation).

The plant weight data was log transformed and then an analysis of variance was performed. Nodding thistle seedlings were significantly larger ($P<0.01$) in the clover only trays (0/5) compared with the treatments that were sown with ryegrass (Fig. 3.24). However, when the treatments that were originally sown with ryegrass (Treatments 3-9) were analysed separately the analysis of variance found no significant differences between them.

A significant ($P<0.001$) exponential relationship was found when the nodding thistle plant weight data was analysed with ryegrass tillers. This relationship accounted for 47.6% of the variation in the data (Fig. 3.25). When the plots sown with ryegrass (Treatments 3-9) were analysed separately no relationship was found between the weights of the nodding thistle plants and the ryegrass tiller density. For both of the above analyses the nodding thistle plant weight data were log transformed.

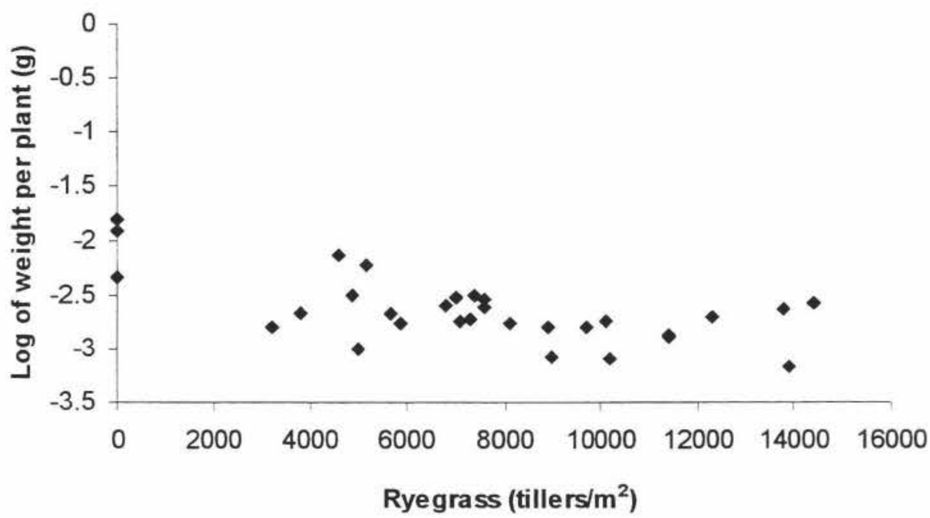

Figure 3.25. The relationship between the size of nodding thistle seedlings (log weight), 20 weeks after sowing, and perennial ryegrass tiller density within the trays.

A significant positive linear relationship ($P<0.05$) was found between the weight of the nodding thistle plants in the trays and the amount of white clover present in the plots (Fig. 3.26). The trend line only accounted for 20.5% of the variation in the data. Both variables were log transformed prior to the analysis.

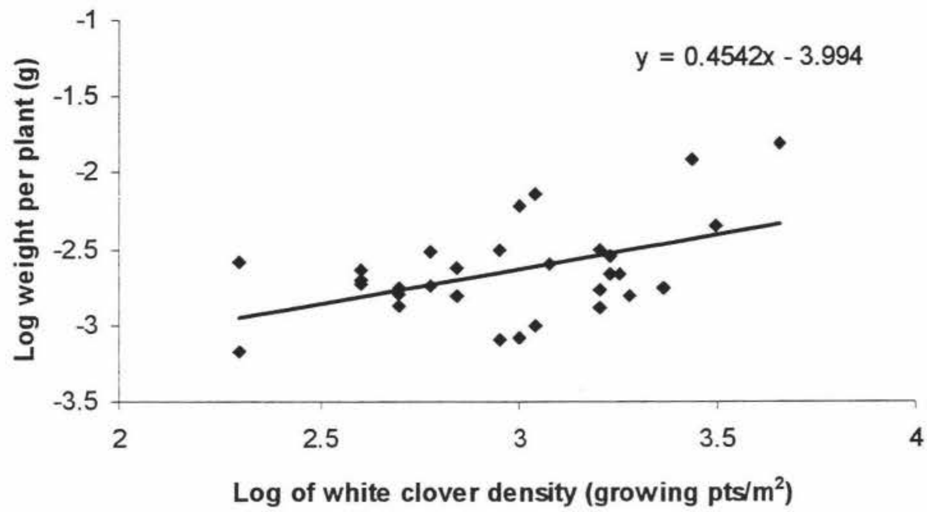

Figure 3.26. The relationship between the size of nodding thistle seedlings (log weight), 20 weeks after sowing, and white clover density within the trays.

3.3.3.3. Timing of seedling emergence

This section investigates the effect of ryegrass tiller density on the timing of weed emergence in the tray experiment. Regression analyses were performed on the percentage of the total emergence that had occurred either at the first count (4 weeks after sowing) or the second count (10 weeks after sowing) depending on emergence rates. The experiment continued for 14 weeks for Scotch thistle and 20 weeks for the ragwort, nodding thistle and hedge mustard, so these counts indicate whether weed seedling emergence occurred earlier in trays with high ryegrass density or in trays with low ryegrass density. The timing of emergence data does not account for mortality, it simply measures the percentage of the total seedlings that emerged by the particular count.

Treatment 1 (0/0) was not included in these regression analyses as this treatment is not a logical part of the progression of increasing ryegrass density.

Scotch thistle - The seedling count data indicated that the Scotch thistle seedlings that emerged in the low-density ryegrass treatments were more likely to emerge earlier (Fig. 3.27). This significant trend ($P<0.001$) for emergence to be delayed as ryegrass tiller density increased, accounted for 39.6% of the variation in the data.

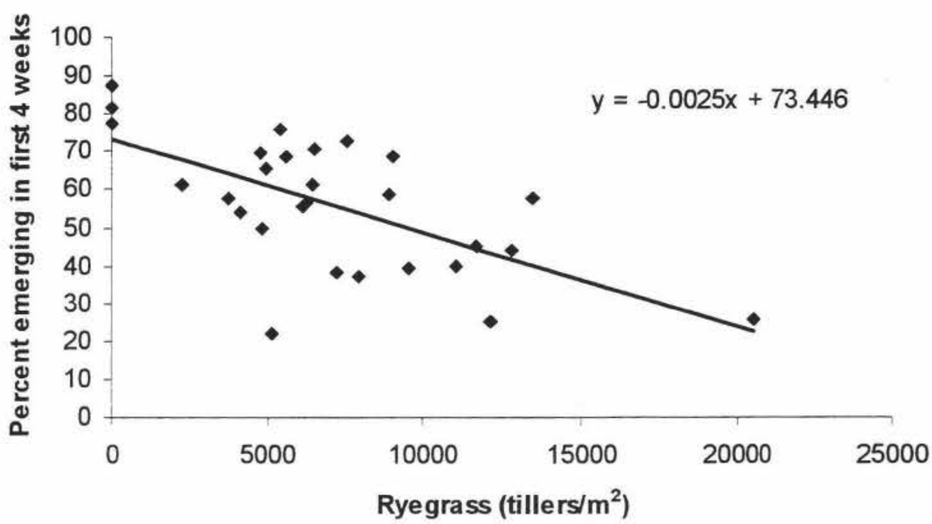

Figure 3.27. The relationship between the percentage of the total Scotch thistle seedling emergence that occurred within the first four weeks after sowing and ryegrass tiller density.

By comparison, at the first count, 61.1% of the total Scotch thistle emergence in Treatment 1 (0/0) had occurred by the first count (4 weeks after sowing). However, Scotch thistle emergence rates were very low in Treatment 1 (Fig. 3.8) in comparison to the other treatments and so this data may not be as reliable as that from the other treatments.

Ragwort - Ragwort emergence was delayed as ryegrass tiller density increased (Fig. 3.28). The percentage of ragwort seedlings that emerged at first count was higher when ryegrass tiller density was lower. The exponential curve fitted to this data accounted for 70% of the variation in the data and was highly significant ($P<0.001$).

In Treatment 1, 79.4% of the total ragwort emergence occurred within the first four weeks of the experiment.

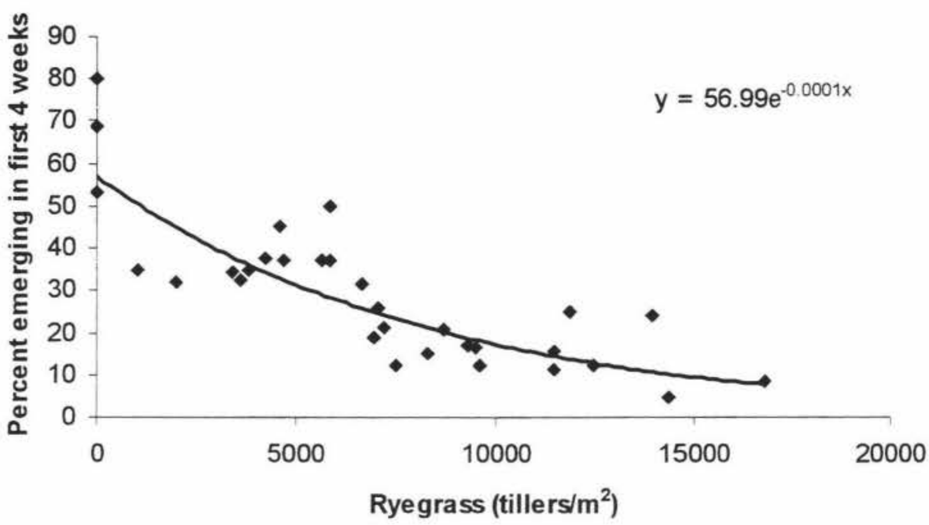

Figure 3.28. The relationship between the percentage of the total ragwort seedling emergence that occurred within the first four weeks after sowing, and ryegrass tiller density.

Hedge mustard - Due to the low levels of hedge mustard emergence in the tray experiment, there was not enough data to do any meaningful analysis. Trays with no hedge mustard emergence were not included on the graph (Fig. 3.29). By comparison, 87.7% of the total hedge mustard emergence in Treatment 1 occurred in the first four weeks of the experiment.

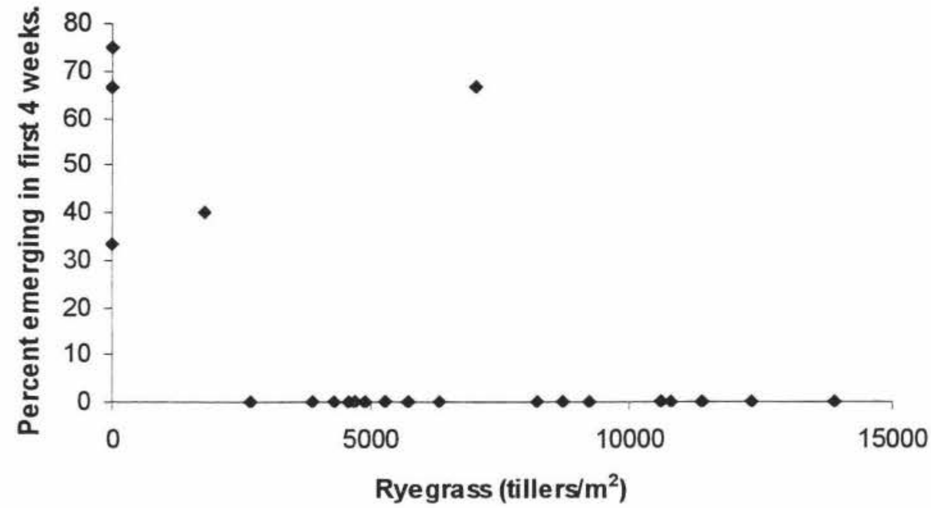

Figure 3.29. The relationship between the percentage of the total hedge mustard seedling emergence that occurred within the first 4 weeks after sowing, and ryegrass tiller density.

Nodding thistle - For the nodding thistle timing of emergence analysis it was necessary to use the data from the second seedling count, 10 weeks after sowing (the final count was 20 weeks after sowing). At the time of the first count 27 of the 35 trays had had no nodding thistle emergence and the data was meaningless.

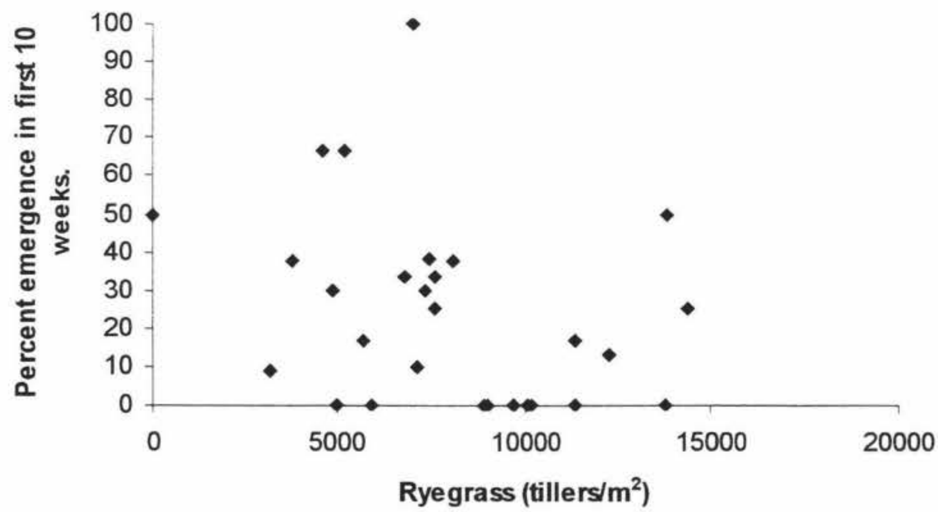

Figure 3.30. The relationship between the percentage of the total nodding thistle seedling emergence that occurred within the first 10 weeks after sowing, and ryegrass tiller density.

Due to the large number of zeros in the data, the nodding thistle seedling count data was analysed by a logit regression. This indicated a significant ($P<0.001$) trend for nodding thistle emergence to be delayed as ryegrass density increased (Fig. 3.30).

3.3.3.4. Mortality

This section investigates the fate of the seedlings that emerged throughout the experiment. The Scotch thistle tray experiment finished 14 weeks after sowing. For the other species, the experiment continued for 20 weeks in total. At this point it was determined how many of the emerging seedlings had died throughout the experiment.

Overall, the number of weed seedlings dying during the tray experiment was very low (Table 3.4). The highest percentage of seedlings lost in the Scotch thistle, ragwort, and hedge mustard experiments was in Treatment 1 (0/0) where the percentage death ranged from 29.6% to 59.2% of the seedlings that emerged. However, for Scotch thistle the 52% death recorded was equivalent to only 1.3 seedlings per tray due to low emergence values in this treatment. As no nodding thistle seedlings emerged in Treatment 1 there was no data for mortality of this species.

For all the species, in the sown treatments (Treatments 2-9) the maximum percentage death recorded was 25% of emerged seedlings. This was observed in Treatment 4 of hedge mustard, however this equated to less than one seedling per tray due to very low emergence. In the sown treatments all species lost less than five seedlings per tray, which in most cases related to less than 5% of the emerged seedlings (Table 3.4).

The best indicator of each sward's ability to resist weed invasion was probably the number of weed seedlings that were present at the end of the experiment. This measure incorporated both seedling emergence and survival. Regression analyses were performed to investigate the relationship between perennial ryegrass tiller density and the number of weed seedlings surviving until the end of the experiment. However, due to the low mortality in the tray experiment (Table 3.3), the analyses performed on the surviving plants gave very similar results to the analysis of emergence and so they are not presented here.

TABLE 3.4. Effect of treatment (pasture sowing rates) on the mean number of weed seedlings dying throughout the tray experiment. Percent mortality figures are in brackets.

Treatment	Scotch thistle	Ragwort	Hedge mustard	Nodding thistle
1 (0/0)	1.3 (52.0%)	27.0 (29.6%)	17.5 (59.2%)	-
2 (0/5)	2.3 (4.2%)	3.0 (3.2%)	0.7 (19.4%)	0.7 (16.7%)
3 (5/5)	1.3 (2.7%)	3.3 (3.1%)	0.0 (0.0%)	1.0 (9.9%)
4 (10/5)	1.0 (2.6%)	4.3 (3.6%)	0.3 (25%)	0.0 (0.0%)
5 (20/5)	0.0 (0.0%)	3.3 (2.1%)	0.0 (0.0%)	0.5 (4.5%)
6 (40/5)	0.3 (0.9%)	3.0 (2.6%)	0.0 (0.0%)	0.0 (0.0%)
7 (80/5)	2.5 (5.5%)	3.3 (3.1%)	0.0 (0.0%)	0.5 (4.2%)
8 (160/5)	0.8 (2.2%)	2.8 (2.7%)	0.5 (16.7%)	0.5 (3.7%)
9 (320/5)	0.8 (2.3%)	2.5 (2.0%)	0.3 (4.2%)	0.3 (6.3%)

3.6. Discussion of tray experiment

3.6.1. Pasture condition when weed seed sown

Pasture composition measurements of the trays, 8 months after sowing the pasture species, showed that perennial ryegrass tiller density was still higher in trays with higher sowing rates (Fig. 3.1). However, this relationship appeared to be asymptotic. It was expected that the curve should be asymptotic as self-thinning (or density-dependent mortality) due to intra-specific competition in the high ryegrass density trays would tend to reduce (over time) the number of tillers present in the plots. An experiment by Lonsdale & Watkinson (1982) also investigated varying plant densities of perennial ryegrass. Their results indicated that perennial ryegrass does obey the -3/2 power law first suggested by Yoda *et al.* (1963). This law states that unshaded plant (or tiller) populations all converge towards a self-thinning line of slope minus 3/2, irrespective of the initial density. This mathematical relationship indicates that as the size (or weight) of a plant (or tiller) increases, the density of the population decreases.

Puckridge & Donald (1967) found similar results when investigating a range of sowing densities of wheat. At the highest densities studied wheat plant numbers declined through self-thinning, from the initial planting density of 5400 plants/m^2 to 1766 plants/m^2 over 26 weeks. The next highest density declined from 1078 to 447 plants/m^2 over the same time period. These results of Puckridge & Donald (1967) indicate that the process of self-thinning is evident in other plant populations. They also indicate that the decline in plant numbers is faster with higher initial densities, due to greater competitive pressure in these treatments.

Perennial ryegrass plants in the low sowing rate plots would not experience the same level of competition for resources, as the plants in the high ryegrass sowing rate trays, and so vegetative reproduction (or tillering) would be occurring. Tillering in the low ryegrass density trays should, over time, cause a similar number of ryegrass tillers to be present in each treatment regardless of the original sowing rates.

The length of time between sowing the pasture species and the perennial ryegrass tiller counts in the current tray experiment allowed plenty of time for both self-thinning and tillering to have an effect on the eventual tiller numbers.

As the perennial ryegrass sowing rate increased, there was a decline in white clover density (Fig. 3.2). This relationship can be described as an exponential decline. White clover density decreased sharply from about 3500 growing points/m^2 (in the plots where no ryegrass was sown) to 1700 growing points/m^2 with the introduction of 5 kg/ha of ryegrass seed. A similar trend was also apparent with the relationship between white clover growing points and ryegrass tiller density (Fig. 3.3). This indicated that the density of white clover was seriously and negatively affected by competition from ryegrass, even when ryegrass was present at low densities. Zaleski (1965) also found that white clover yield (in this case number of seed heads) was reduced by increasing the sowing rate of perennial ryegrass.

Although white clover appears to be out-competed by swards of dense ryegrass it is unlikely that the clover would disappear completely from the sward. Turkington & Harper (1979) have suggested that perennial ryegrass and white clover do not exclude each other due to temporal niche separation. They discovered that ryegrass has a major peak of leaf production from March to June and then again in August-September, whereas white clover tends to have peak growth in July (dates refer to Northern Hemisphere). This difference in growth periodicity allows the two species to cohabit and prevents competitive exclusion.

The continual removal of volunteer weeds and grasses from the trays reduced the competition exerted by other species. However, the white clover that was sown in Treatments 2-9 would have provided some competition for the establishing ryegrass plants. It is unlikely that the effect of this species would have been large due to the more prostrate growth form of white clover in comparison to ryegrass. The faster growing, taller perennial ryegrass will intercept much of the available resources, i.e. water, light and nutrients, leaving the white clover at a disadvantage. Interference experiments by Turkington & Jolliffe (1996) support this conclusion as they discovered that perennial ryegrass had a greater effect on itself than white clover had on perennial ryegrass.

3.6.2. Weed results

Overall, the germination tests on the weed seeds indicated low germination rates (Table 3.2). Viability tests were not completed on the seed that failed to germinate and as such it was not determined whether these seeds were dormant or dead. However, the germination tests were designed primarily to give an indication of the viability to determine an appropriate number of seeds to sow into the trays. The results from the tray experiment indicated that the weed seeds were more viable than the germination tests suggested. Up to 52% of the Scotch thistle seed sown into the trays germinated in the 14 weeks that the experiment was run. Ragwort emergence recorded in the trays was up to 43% of the seeds sown. Again this value is much higher than was indicated by the germination tests. The results from Scotch thistle and ragwort emergence in the trays indicate that there was a level of dormancy in the seed, especially as some seed would have been prevented from germinating due to pasture cover. Therefore, it would seem that the germination tests conducted prior to the experiment did not give an accurate assessment of seed viability. Both nodding thistle and hedge mustard emergence in the trays was lower than the potential germination indicated by the germination tests, suggesting that these species were more affected by the pasture cover than ragwort or Scotch thistle or ragwort. This comment is especially relevant to hedge mustard as 70%

germination was recorded in the laboratory germination test. However, the nodding thistle seed had a maximum germination of 16.7% in the laboratory tests compared with 4.4% in the tray experiment. Therefore, it would seem that this batch of nodding thistle seed had a low viability and care must be taken interpreting the results.

3.6.2.1. Scotch thistle

Very low emergence values were recorded for Scotch thistle in Treatment 1 (Fig. 3.8). The lack of pasture species in this treatment means that the low emergence values in Treatment 1 cannot be attributed to insufficient light quantity or quality to start the germination process. The seeds for this treatment were sown on top of the soil and were not mixed into the soil profile. In this situation the seed could have been subject to wetting during rain or watering and then potentially a drying cycle due to the lack of protective vegetation. Doucet & Cavers (1996) found that wetting and drying of Scotch thistle seeds could delay germination when compared to seed that was not subject to a drying episode. They discovered that after five days 97% of the seeds that did not experience a drying episode had germinated compared to 78% of the seeds that were subject to a drying episode. For the experiment reported by Doucet & Cavers (1996) there was only one drying episode before the germination test. The effects of drying cycles could well be more pronounced if there are repeated cycles of wetting and drying of the Scotch thistle seed, as could have been experienced by Scotch thistle seed in Treatment 1 of this current experiment. If this is the case then the seeds in Treatment 1 of the current experiment could have lower emergence rates for this very reason.

Amongst the other treatments there was a general decrease in Scotch thistle emergence as ryegrass tiller density increased (Fig. 3.9) and emergence was also delayed as ryegrass tiller density increased (Fig. 3.27). Wardle *et al.* (1992) also found that the percentage emergence of Scotch thistle was very strongly related to pasture cover. These results could be explained by decreased light levels on the soil surface as ryegrass density increased. Both Doucet & Cavers (1996) and Grime *et al.* (1981) have reported that imbibed Scotch thistle seed that is left in the dark can develop an induced dormancy. This can prevent seeds from germinating when located in deep shade. As ryegrass tiller density increases, the likelihood of a particular seed experiencing deep shade increases and therefore it is possible that this mechanism is both reducing the amount of Scotch thistle emergence and delaying the onset of germination at high ryegrass densities. The decline in total emergence is not significant if Treatment 2 (0/5) is removed from the analysis, suggesting that the presence of ryegrass negatively affects Scotch thistle emergence regardless of the density. This may indicate that there is only a small amount of variation in light levels on the soil surface at different ryegrass densities.

The Scotch thistle seedlings that were harvested from Treatment 2 (0/5) had the heaviest mean weight out of all the treatments (Fig. 3.16). This treatment had no perennial ryegrass and the highest density of white clover. The regression analysis examining the relationship between white clover density and Scotch thistle weights indicates that as the density of white clover increases the weed seedlings get heavier. However, this relationship is probably more indicative of the Scotch thistle weights declining as ryegrass density increases rather than indicating a positive effect of white clover on weed size, as throughout the treatments (excepting Treatment 1) as white clover density decreased the amount of perennial ryegrass present increased. This finding is similar to that of Wardle *et al.* (1992). They experimented with sowing Scotch thistle and nodding thistle into pure established swards of grasses and legumes in a glasshouse. They also discovered that perennial ryegrass had a significantly greater negative effect on thistle diameter than did white clover. It is important to note that the clippings from the monthly trim of the pasture sward were not returned to the trays and so higher clover densities and the subsequent higher rates of nitrogen fixation by the clovers in these trays are unlikely to have contributed additional fertiliser for the weed species. Even if there was some additional nitrogen in the trays with low ryegrass densities it is unlikely that this would be purely beneficial to the thistle as the perennial ryegrass would also benefit and thus become more competitive.

Treatment 1 had the second heaviest Scotch thistle seedlings and this could easily be explained by the absence of competition for resources (i.e. light, nutrients and water) from pasture plants. Despite the lack of competition, the Scotch thistle seedlings in this treatment may not have grown as much as those in Treatment 2 as these seedlings had no surrounding vegetation to protect them from physical damage from wind, rain, frosts etc. With the other treatments, as the ryegrass tiller density increased the Scotch thistle seedling weights decreased (Fig. 3.17), suggesting that competition from the pasture plants increased as ryegrass tiller density increased. This trend is strongly influenced by one point and becomes non-significant without it. However, it would appear that ryegrass provides more competition for the emerging Scotch thistle seedlings than white clover although there are limited differences in competitive pressure on these seedlings between trays with low ryegrass density and trays with a high density of ryegrass.

Very few Scotch thistle seedlings died during the tray experiment (Table 3.4). The highest mortality was recorded in Treatment 1 where over half of the seedlings that emerged died. However, due to the very low emergence values for Scotch thistle in this treatment, this accounted for only 1.3 seedlings dying per tray. The lack of protective vegetation to shield the emerging seedlings from climatic extremes, i.e. frosts, heavy rain etc., could help to explain the high mortality in this treatment.

Arguably the most important measure of how ryegrass density affects Scotch thistle is the overall analysis of how many weeds were present at the end of the experiment. This measure takes into account emergence and death and gives an overall measure of how well different densities of ryegrass resist weed invasion. As ryegrass tiller density increased the number of plants alive at the end of the experiment decreased. Therefore it would appear that the high densities of ryegrass provided more competitive pressure on the Scotch thistle seedlings making it more difficult for them to emerge and survive and thus reducing the size of the Scotch thistle population in dense pasture.

3.6.2.2. Nodding thistle

Very low nodding thistle emergence was recorded in all of the experimental trays (Fig. 3.14). The percentage of nodding thistle germinating in the laboratory test was only 6.2% (Table 3.2) however this is still larger than the emergence values gained in the trays. By comparison both Scotch thistle and ragwort had more emergence in the trays than was recorded in the germination tests. This suggests that nodding thistle emergence is more negatively affected by dense pasture swards than ragwort or Scotch thistle. These very low germination and emergence rates recorded in both the germination tests and the tray experiment indicate that the nodding thistle seed used in the experiment had very low viability and as such may have resulted in seedlings with lower vigour than would have occurred with a more viable seed lot.

Similarly low levels of nodding thistle emergence have been found by other researchers. In a similar experiment Wardle *et al.* (1992) found that established swards of perennial ryegrass substantially inhibited the emergence of nodding thistle but had little effect on Scotch thistle emergence. Kelly & McCallum (1990) also found very low emergence values for nodding thistle in established swards. In their experiment nodding thistle germination percentages ranged from 0.1% to 6% depending on the length of the sward (lower emergence in long swards). It has been suggested that vegetation filtered light has a negative influence on nodding thistle seed germination (Medd & Lovett 1978, Popay & Medd 1990) and that subsequently nodding thistle seed covered by a dense sward may remain dormant for long periods (Popay & Thompson 1979). Therefore, it is possible that nodding thistle germination in the established swards in the trays (i.e. Treatments 2-9) was hindered by the low light levels present under the established vegetation. This however, doesn't explain the complete lack of nodding thistle emergence in the bare ground trays (Treatment 1).

Nodding thistle germination has been found to be limited by low temperatures. Experiments by Groves & Kaye (1989) indicated that temperatures fluctuating between 15°C and 0°C significantly limited germination of nodding thistle seed. The average air temperatures throughout the duration of the tray experiment varied from 5.2°C (average minimum) to 14.9°C (average maximum) (see Section 3.3.2). The average minimum temperature of the grass during the experiment was 2.1°C (compared to 5.2°C for the air) and so the temperatures that the seeds experienced would probably have been lower than that indicated by the air temperature, preventing the germination of some seed. Nodding thistle seed in Treatment 1 had no protection from climatic extremes due to the absence of vegetation and therefore may have been more influenced by these low temperatures. Nodding thistle experiments by Wardle *et al.* (1995) indicated that emergence in the bare ground plots was highly variable. At times they recorded emergence values in the bare ground plots to be an order of magnitude lower than that recorded under grass cover. They also postulated that micro-climatic extremes might have been a factor.

Another possible explanation for the low rates of both nodding thistle and Scotch thistle emergence in Treatment 1 could be seed predation by birds or mice. Both of these weed species have relatively large seeds that would be easy to spot on a bare soil surface and so it is possible that the high emergence rates expected in the bare ground trays did not occur due to the loss of seed to predators. Kelly & McCallum (1990) excluded mice and birds from pasture sown with nodding thistle seed using wire cages. They discovered 81% fewer seedlings and dormant seeds present in the plots with no protection compared to the plots with the wire cages. They estimated that seed loss in their experiment was very high as even within the caged plots only 28% of the sown seeds were accounted for. They suggested that invertebrate seed predators, fungal attack and non-viable seeds were the cause of this additional seed loss.

It is unlikely that the low emergence values recorded for Scotch thistle and nodding thistle in Treatment 1 was due to seedlings emerging and dying in between the seedling counts. The large size of the cotyledons of these two species made their appearance obvious and the trays were examined regularly for nutrient application and watering.

There were no significant trends when ryegrass density was analysed with nodding thistle emergence when all of the data points were included (Fig. 3.15). However, there was a trend for emergence to increase as ryegrass tiller counts increased once an outlier was removed. Removing this outlier is hard to justify as it was a genuine result, so it may be more valid to say that nodding thistle emergence was not affected by varying perennial ryegrass density. Wardle *et al.* (1992) also found no correlation between sward cover and nodding thistle emergence.

As with Scotch thistle, nodding thistle emergence tended to be delayed as ryegrass tiller density increased (Fig. 3.30). This trend can again be explained through higher light levels in low ryegrass density trays. Popay & Thompson (1979) discovered that nodding thistle seed covered by a dense sward could remain dormant for long periods of time. If this is the case then nodding thistle seed sown into the high ryegrass density plots would be more likely to become dormant and thus emerge later than seed sown into low ryegrass density plots. Wardle *et al.* (1992) also found a significant negative correlation between sward cover and the speed of nodding thistle emergence. This indicates that the pasture canopy influenced light quality on the soil surface.

The seedlings harvested from Treatment 2 were significantly heavier than those harvested from the trays sown with ryegrass (Fig. 3.24). Once again this is probably due to the lower amount of competition experienced by the seedlings due to the absence of ryegrass in this treatment. Wardle *et al.* (1992) also found that legumes had less of a negative effect on nodding thistle size than grasses. Out of the ten pasture species they tested (6 grasses, 4 legumes) white clover had the least negative effect on the thistle size.

There was no relationship between nodding thistle plant weights and ryegrass tiller density once Treatment 2 was removed (Fig. 3.25), suggesting that the density of the ryegrass is not as important as the presence of it. However, one factor that these tiller density measurements do not take into account is the size of the individual tillers within the trays. Trays that contain low numbers of ryegrass tillers may contain tillers of a larger average size; thus the actual competitive pressure exerted by the ryegrass may not wholly be related to density as size may also be a factor. If that is the case then the competitive pressure exerted by the ryegrass could be similar in all treatments.

One other possible explanation for nodding thistle achieving a lesser size in the perennial ryegrass swards than the clover only swards could be due to an allelopathic effect from perennial ryegrass on nodding thistle. Wardle *et al.* (1991) found that soil collected from underneath an established perennial ryegrass sward inhibited both nodding thistle emergence and growth. In the same study soil collected from beneath an established white clover sward exhibited a stimulatory effect on nodding thistle growth, presumably due to the increased nitrogen in the soil. However, in the current experiment it is more likely that the lower nodding thistle weights can be attributed to competition from the perennial ryegrass.

With the sown treatments there was no more than one seedling dying per treatment and no trends were apparent with all of the data included. Therefore, mortality of the nodding thistle seedlings was unaffected by ryegrass density in the timeframe of this experiment.

3.6.2.3. Ragwort

There was a significant trend for ragwort emergence to increase as both ryegrass sowing rate (Fig. 3.10) and tiller density increased (Fig. 3.11). This result is contrary to what was expected. Light has been proven to stimulate the germination of ragwort seed (van der Meijden & van der Waals-Kooi 1979) and it was assumed that both light quality and quantity would be lower in the high density ryegrass trays and thus ragwort germination would be negatively affected in these trays. There are several possible explanations for this result including, similar competitive pressure in all treatments, ryegrass clumping allowing germination in pasture gaps, light allowed onto the soil surface when the sward was trimmed or severe frosts inducing dormancy in ragwort seed.

It is possible that 8 months after the pasture species were sown that competitive pressure was similar in all treatments due to the increased density of white clover in the low ryegrass sowing rate trays and the relatively larger size of the ryegrass tillers in the trays with a low ryegrass density. The amount of white clover present in the low ryegrass density trays is much higher than that present in the high ryegrass density trays (Fig. 3.2). Therefore it is possible that the overall plant density present in the different treatments could be similar, with the only difference being the source of the competition for the emerging ragwort seedlings (i.e. either from ryegrass or clover) (Armstrong *et al.* 2001). This suggests that ragwort emergence is more negatively affected by white clover density than perennial ryegrass density. This may be a valid point as Harper & Wood (1957) have argued that clover may be a stronger competitor than ryegrass for emerging ragwort seedlings due to their similar growth form.

The intraspecific competition at high sowing rates of perennial ryegrass leads to a large number of thin tillers. Conversely, at low ryegrass sowing rates, tillers have more space and resources for development and therefore tend to attain a larger size. Presumably larger tillers exert more competitive pressure on emerging ragwort seedlings. Tiller density measurements do not take into account size of tillers and therefore do not give the full picture of the competitive pressure exerted by the ryegrass.

Ryegrass tiller density figures suggest that the trays are an even density throughout. However, this is obviously not the case. The ryegrass was in reality unevenly spaced so that both clumps of dense ryegrass and gaps in the sward were present. There is a possibility that the ragwort emergence was in fact higher in the high density ryegrass trays due to the majority of the germination in these trays occurring in gaps in the sward.

There is also a possibility that the regular (monthly) cutting of the pasture species down to a level of 3cm enabled adequate light to penetrate the sward to stimulate germination. The pasture plants in the trays were trimmed prior to sowing the ragwort seeds. This too could have provided enough light to stimulate germination early on in the experiment.

During the experiment, the Ruakura Research Centre experienced a series of very heavy frosts (Fig. 3.6). Experiments by van der Meijden & van der Waals-Kooi (1979) have indicated that a short period of frost after contact with water leads to an induced dormancy in ragwort seed that may last for some weeks. The ragwort seeds sown into low density ryegrass trays may have experienced these frosts to a greater degree than seeds in the high density ryegrass trays which would have had a greater degree of protection from the elements. If this was the case then seed in the lower density plots could have experienced a delay in germination and due to the relatively short length of the tray experiment (20 weeks) the seeds in the low density ryegrass treatments may not have recovered from the temporary dormancy in time to germinate within the experimental time-frame.

In reality a combination of the above scenarios may have had an effect on ragwort emergence in the tray experiment, thus causing the unusual result of increased ragwort emergence in swards with high densities of ryegrass.

Ragwort emergence was increasingly delayed as ryegrass tiller density increased (Fig. 3.28). Ragwort seed germination is influenced by light quality (van der Meijden & van der Waals-Kooi 1979, Wardle 1987). Dense swards of perennial ryegrass could filter out much of the incoming light before it reached the soil surface and so ragwort seeds in these treatments may well experience delayed germination due to a lack of sufficient light. The seedlings in Treatment 1 tended to emerge sooner than the other treatments. This also suggests that light levels were an important factor in determining when the ragwort seedlings would emerge.

Another possible scenario is that the lower light levels experienced over the winter months caused a greater amount of self-thinning to occur. This could have freed up more germination sites for the ragwort seed and thus allowed germination to occur. Kays & Harper (1974) experimented with high densities of perennial ryegrass growing with different levels of light. They discovered that the yield per square metre attained from the plots with low light levels was lower than from plots with higher light levels.

The ragwort plants in Treatments 1 and 2 were significantly heavier than those in the treatments sown with ryegrass (Fig. 3.19). The ragwort seedlings in Treatment 1 grew larger than other treatments (except Treatment 2) due to the absence of competition for resources like water, light and nutrients. Although it was suggested earlier in this section that white clover may be a stronger competitor against ragwort than perennial ryegrass it would appear that once the seedlings have emerged that dense swards of perennial ryegrass compete against ragwort more effectively thus enabling the ragwort seedlings in the clover only plots to gain a larger size.

When the treatments sown with ryegrass were analysed separately, neither the sowing rate nor the density of ryegrass tillers had any effect on the eventual size of the ragwort seedlings. Therefore it appears that the presence of an established mixed sward of ryegrass and clover is much more effective at limiting the size of ragwort plants than is a clover only sward or bare ground.

Ragwort mortality was highest in Treatment 1 (Table 3.4). This is again presumably related to the absence of protection from the elements that emerging seedlings in the bare ground treatment experience. However, the total number of ragwort seedlings surviving to the end of the experiment is positively correlated with the ryegrass tiller density, and therefore it would seem that the denser the sward, the larger the population of ragwort plants will be. This result was unexpected as it was predicted that the ragwort population would decrease as competitive pressure from the ryegrass increased. However, as mentioned earlier the competitive pressure that the ragwort seedlings are exposed to may be similar in all treatments due to the increased white clover density and the increased ryegrass tiller size in the low ryegrass sowing rate plots.

Another point to consider is that due to the higher ragwort emergence in the high ryegrass density plots and the low mortality in the experiment, it is understandable that the number of plants surviving increases in the high ryegrass density plots.

3.6.2.4. Hedge mustard

The highest hedge mustard emergence values were recorded in Treatment 1 (Fig. 3.12). In all the other treatments there was minimal emergence and it would appear that the presence of any vegetation (either ryegrass or clover) prevented hedge mustard emergence. The density of ryegrass tillers had no effect on hedge mustard emergence, indicating that the presence of vegetation is more important than the density of that vegetation. Experiments by Bouwmeester & Karssen (1989) have indicated that the germination of hedge mustard seed is absolutely light dependent and that no germination occurred under dark conditions. Although light levels experienced beneath a pasture sward could hardly be referred to as dark, since germination of hedge mustard seed is so totally dependent on light it is possible that seed sitting underneath a vegetation canopy is not experiencing sufficient light levels for germination to be initiated. This suggestion is supported by the work of Hilhorst (1990) who found that as light intensity increased hedge mustard germination increased. Therefore it would seem that the presence of any vegetation shades the soil surface sufficiently to prevent germination.

The high light levels present in the bare ground plots may have enabled germination to be initiated earlier, compared to the other treatments with a dense sward (Fig. 3.29). Bouwmeester & Karssen (1989) also discovered that the desiccation of hedge mustard seed prior to testing enhanced germination, due to a dormancy breaking effect. They postulated that this related to the detection of vegetation gaps as seed desiccation is more likely to occur on a bare soil surface due to higher incidence of exposure to drying influences like sun and wind, than under vegetation. This factor may also help to explain why the highest and earliest germination in the experiment was experienced in Treatment 1.

The weight of hedge mustard seedlings was highest in Treatment 1 (the bare ground plot) (Fig. 3.22). Hedge mustard appears to flourish when no competition is present and to suffer considerably in a dense sward. Treatment 2 also had relatively heavy seedlings present in the trays, indicating that although the presence of any vegetation will prevent hedge mustard emergence perennial ryegrass is a stronger competitor than white clover. As soon as ryegrass is sown into the plots the size of the seedlings becomes negligible. Although there was a significant negative relationship between ryegrass tiller density and hedge mustard seedling weight, this trend is not significant when Treatment 2 was removed from the analysis. This indicates that the presence of ryegrass is the important factor in reducing hedge mustard size, not the amount or density of the ryegrass. This could also indicate that ryegrass is equally competitive at all sowing rates in the trays, as at lower densities of ryegrass the individual tillers may have been a larger size thus being more competitive than their density would suggest.

Hedge mustard mortality was highest in Treatment 1 (Table 3.4), probably relating to the lack of protection from the elements i.e. frost, heavy rain etc.

3.4.3. Summary

Overall it would appear from the results of the tray experiment that generally dense swards of perennial ryegrass tend to decrease the resultant weed population. For the two thistle species, at high ryegrass densities, emergence was reduced and delayed and the size of the weeds was reduced. Hedge mustard was the most dramatically affected, with the presence of any vegetation (i.e. ryegrass or clover) resulting in negligible emergence. Unusual results were recorded for ragwort whereby emergence increased with increasing densities of perennial ryegrass, however the timing of ragwort emergence was delayed and the seedlings were lighter with dense swards of ryegrass.

Once again it is important to remember that the nodding thistle seed had very low viability and so may not have behaved in the same way as an "average" set of nodding thistle seed. Therefore it is important not to read too much into the nodding thistle results.

These three factors (total emergence, timing of emergence and weight of seedlings) would have a large effect on the resultant weed population. Only a small percentage of weed seedlings that emerge will ever survive to reproduce and therefore the more seedlings that emerge in a pasture the greater the likelihood of one surviving to flowering. The size of the weed seedlings is important as larger seedlings are more likely to survive physical damage from grazing animals and also are in a better situation to capture more of the available resources, i.e. light, water, nutrients. The timing of emergence is also important. Many weed species set seed in autumn and therefore any delay in seedling emergence could cause germination to occur in winter when the likelihood of damaging frosts is increased. Also, the greater amount of rain generally experienced in the winter months, coupled with the lower rates of evaporation and transpiration, keep the soil moisture levels higher and thus make weed seedlings more prone to damage from the treading of grazing animals.

Effect of Varying Sowing Rates of Perennial Ryegrass on Weed Invasion in Established Pasture - a Field Experiment.

4.1. Introduction

The aim of this experimental program was to determine whether there is any ongoing advantage, with respect to reducing weed invasion, in high sowing rates of perennial ryegrass once the pasture has established. This experiment is very similar to the tray experiment (Chapter 3) in that seeds of four weed species, Scotch thistle, nodding thistle, ragwort and hedge mustard, were sown into established swards of perennial ryegrass. These swards were established in field plots and were originally sown with different seeding rates. The primary difference between this experiment and the tray experiment is that volunteer broadleaved weeds and grasses were not removed from the field plots in an attempt to mimic a realistic pasture situation. The other major difference is that the field plots were grazed by cattle and this introduces more variation in the data due to treading, dung, urine and uneven grazing. However, weeds and grazing effects are inevitable in pastures and therefore this field experiment provides a more realistic indication, than would the tray experiment, of how swards with different perennial ryegrass sowing rates will resist weed invasion.

Thus the following experiment has the same objectives as the tray experiment. The first was to investigate whether the original sowing rates of perennial ryegrass and white clover had any influence on the resulting weed population i.e. emergence, the timing of emergence, and mortality. The second objective was to investigate whether the ryegrass tiller density at the time of sowing of the weed seeds had any effect on the same variables. Treatment 1 was not included in the second objective as it not a logical part of the progression of increasing ryegrass densities.

4.2. Materials and methods

4.2.1. Establishment of pasture swards in field plots

The pasture used for the field experiment was established at the Ruakura Research Centre, Hamilton on 14 April 1999, in a paddock that had been in kale (*Brassica oleracea*) the previous year. The paddock was ploughed and harrowed and then 28 plots measuring 3m x 7m were established. Perennial ryegrass (cv. Bronsyn) and white clover (50:50 mix of cv.s Sustain and Aran) seed were hand sown onto the plots. After sowing the plots were raked to ensure even distribution of the seeds within each plot and then rolled.

Seven treatments were established involving different sowing rates of perennial ryegrass. The rates were 0, 5, 10, 20, 40 and 80 kg/ha of ryegrass seed, all with 5 kg/ha of white clover seed. There was also a treatment that had no pasture species sown into it (Table 4.1). The treatments were arranged in a randomised complete block design, with four replications of each treatment. The plots were grazed by Jersey calves as required. Emerging volunteer plants were left in the plots to mimic a realistic pasture situation.

Table 4.1. The sowing rates of perennial ryegrass and white clover sown in field plots on 14th April 1999 (12 months prior to sowing seeds in the weed experiment).

Treatment	Ryegrass sowing rate (kg/ha)	White clover sowing rate (kg/ha)
1	0	0
2	0	5
3	5	5
4	10	5
5	20	5
6	40	5
7	80	5

For the weed seed germination test results refer to Section 3.2.2.

4.2.2. Introduction of weed seeds

On 18 April 2000, 12 months after sowing the pasture species, four sub-plots measuring 200 mm x 250 mm, were randomly located in each plot and permanently marked. Within a plot, each sub-plot was sown with a different weed species, either nodding thistle (500 seeds), Scotch thistle (250 seeds), hedge mustard (500 seeds) or ragwort (500 seeds). The weed seeds were evenly scattered into the sub-plots by hand. In the same week, ten cores (each 50 mm diameter) were taken at random from each plot and for each core, perennial ryegrass tillers, white clover growing points, weed surface area, and the tillers of volunteer grasses were estimated. Immediately before and after every grazing the position of each individual sown weed seedling was mapped to enable the fate of each seedling to be followed (refer to 3.2.2 for full description). The experiment continued for 7 months (until 22 November 2000) by which time most of the sown weed seedlings had disappeared. Due to the low levels of survival in the field experiment seedling weights were not recorded.

4.3. Results

It is important to note that Treatment 1 was originally not sown with any pasture species (as in the tray experiment). However, in the field experiment Treatment 1 can not be considered a "bare ground" plot due to the presence of broad-leaved weeds and volunteer grasses.

As in Chapter 3, throughout the analysis of these experiments, it was necessary to deal with Treatment 1 differently. Treatment 1 was originally not sown with any pasture species (Table 4.1), and so was not a logical part of the progression of increasing rates of ryegrass. Therefore, it could not be included in any regression analysis. Instead, an ANOVA was performed using treatment number (to separate the two zero ryegrass plots) to determine any differences between Treatment 1 and the others. Then it was removed and the other treatments could be analysed together.

For climate data for the field experiment, refer to Section 3.4.

4.3.1. Pasture condition when weed seeds sown.

As the ryegrass sowing rate increased, the number of ryegrass tillers present in the plots also increased (Fig. 4.1). However, the curve appeared to be flattening off at the higher sowing rates. When an exponential curve was fitted to this data, with a square root transformation on the ryegrass tillers, the trend was shown to be highly significant ($p=0.001$) and accounted for 43% of the variation in the data.

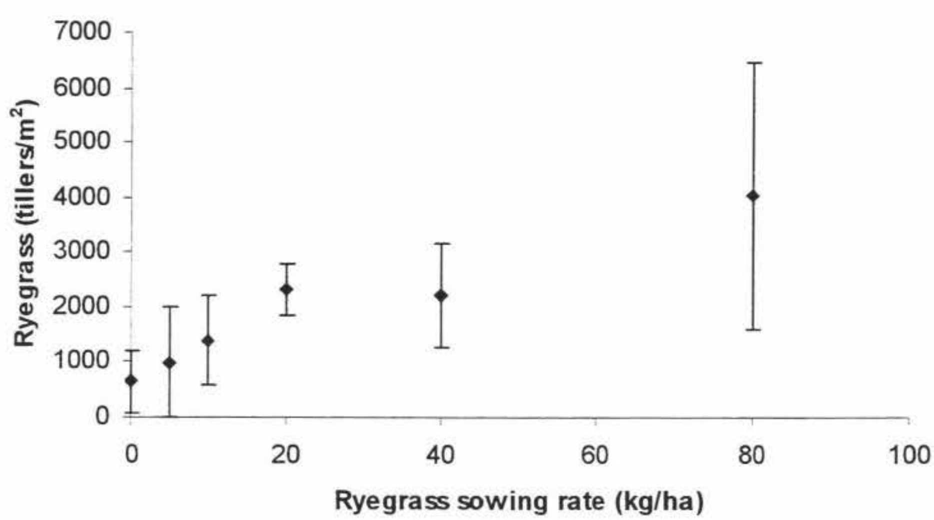

Figure 4.1. The relationship between ryegrass tiller density and ryegrass sowing rate (12 months after pasture sowing) in field experiment (error bars indicate standard deviation).

As the ryegrass sowing rate increased, the number of white clover growing points present in the plots decreased (Fig. 4.2). The analysis of variance indicated that Treatment 1 (0/0) had significantly ($P<0.001$) more white clover growing points than any of the treatments. Thus ironically the only plot which had no clover seed sown into it for this experiment had the most white clover growing points present 12 months later.

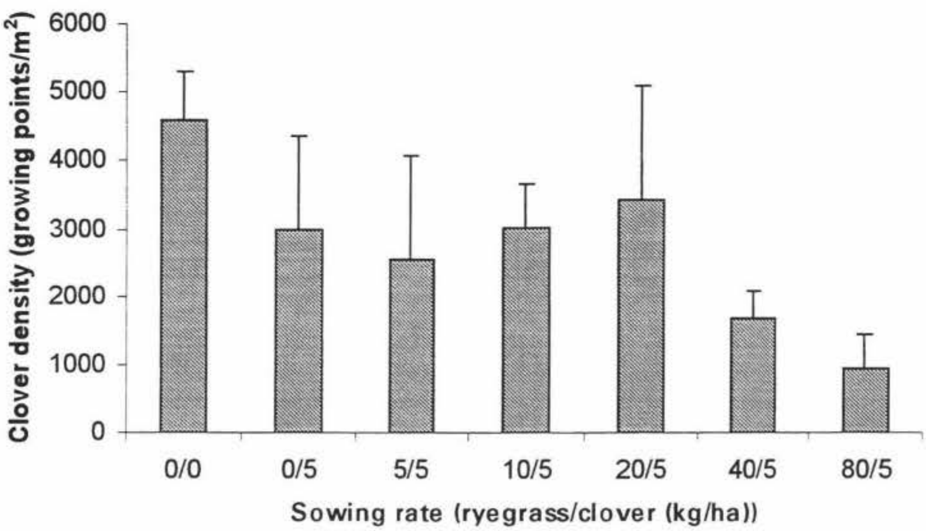

Figure 4.2. Effect of ryegrass sowing rate on white clover growing points (12 months after pasture sowing), in the field experiment (error bars indicate standard deviation).

There was no significant relationship between the density of white clover growing points and ryegrass tiller density 12 months after sowing the field experiment (Fig. 4.3). Treatment 1 (0/0) was not included in this analysis.

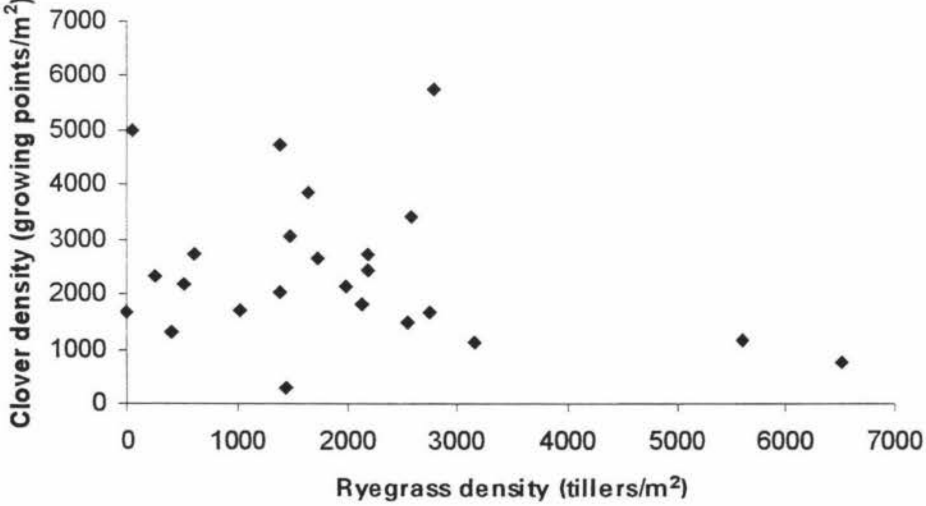

Figure 4.3. The relationship between ryegrass tiller density and white clover density (12 months after pasture sowing), in the field experiment.

There were a number of broad-leaved weeds present in the plots 12 months after sowing, especially at ryegrass sowing rates below 10 kg/ha (Fig. 4.4). An analysis of variance showed that Treatments 1 (0/0), 2 (0/5) and 3 (5/5) had significantly ($P<0.05$) more weeds than the higher density ryegrass treatments.

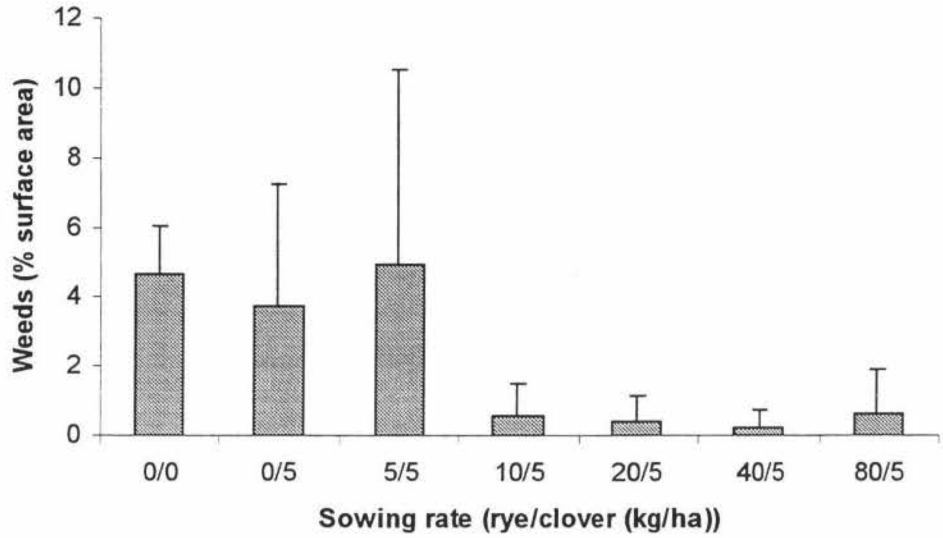

Figure 4.4. Effect of sowing rate on the presence of broad-leaved weeds (12 months after pasture sowing), in the field experiment.

Although there was a trend for the amount of weeds to decrease as ryegrass tiller counts increased, there was no significant correlation between these two variables (Fig. 4.5). The most common broad-leaved weeds present in the field plots were broad-leaved dock (*Rumex obtusifolius*) and narrow-leaved plantain (*Plantago lanceolata*). Other weeds present at low levels were: creeping oxalis (*Oxalis exilis*), dandelion (*Taraxacum officinale*), and fiddle dock (*Rumex pulcher*).

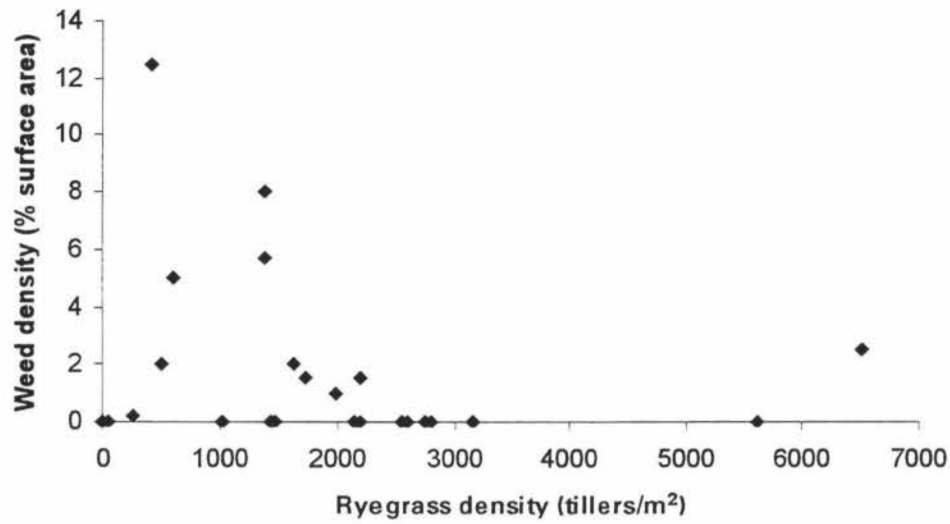

Figure 4.5. The relationship between ryegrass tiller density and the amount of broad-leaved weeds present (12 months after pasture sowing) in the field experiment.

As the perennial ryegrass sowing rate increased, the amount of volunteer grasses decreased (Fig. 4.6). Using treatments as factors an analysis of variance showed Treatment 1 (0/0) had significantly more ($P<0.001$) volunteer grasses than all treatments sown with ryegrass (Treatments 3-7). However, the amount of volunteer grass present in Treatment 1 was not significantly greater than found in Treatment 2 (0/5). The two most common volunteer grass species in the field plots were annual poa (*Poa annua*) and browntop (*Agrostis capillaris*).

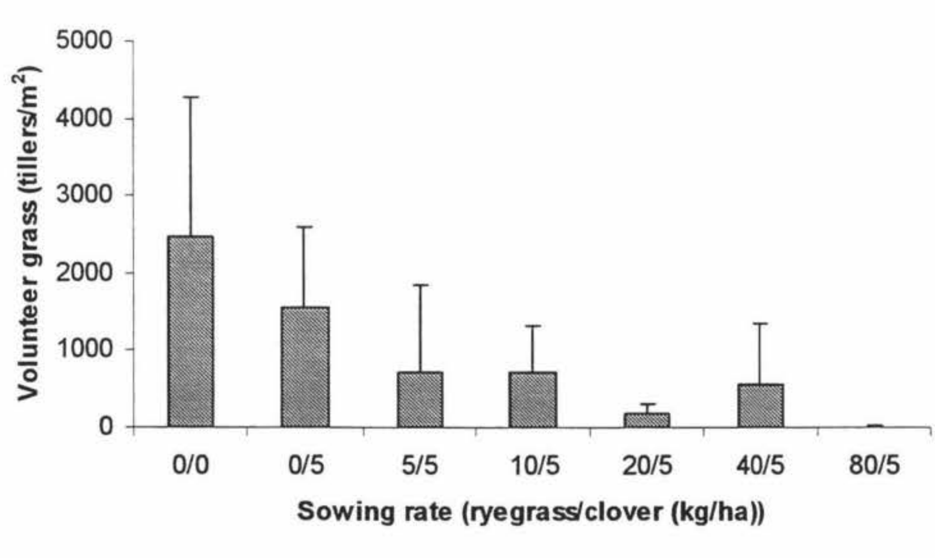

Figure 4.6. Effect of sowing rate on presence of volunteer grasses (12 months after pasture sowing) in the field experiment (error bars indicate standard deviation).

When an analysis of variance on volunteer grass tillers (including seedlings) was performed against treatment, a significant linear trend ($P<0.001$) was found (Fig. 4.7) indicating that as the treatment number increased, the amount of volunteer grass decreased. The volunteer grass data was log transformed prior to the analysis.

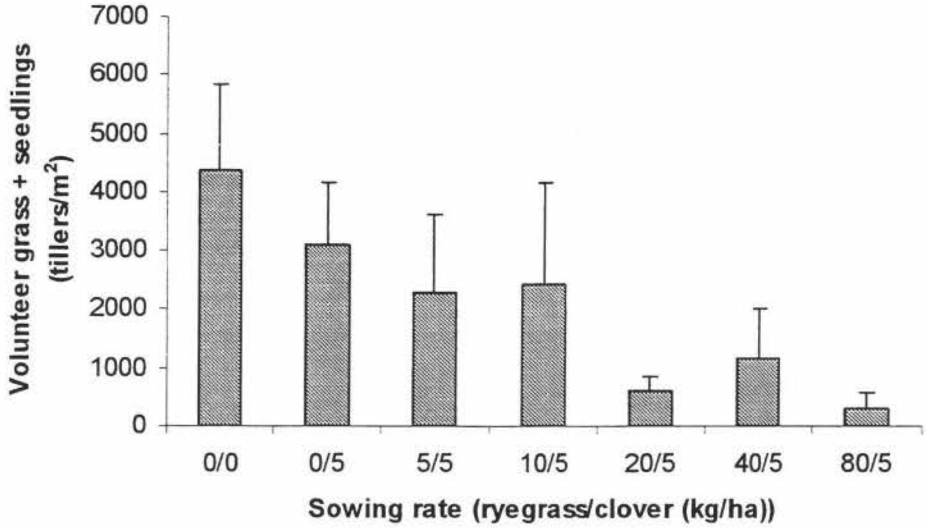

Figure 4.7. Effect of sowing rate on the presence of volunteer grasses (including grass seedlings), 12 months after pasture sowing, in the field experiment (error bars indicate standard deviation.

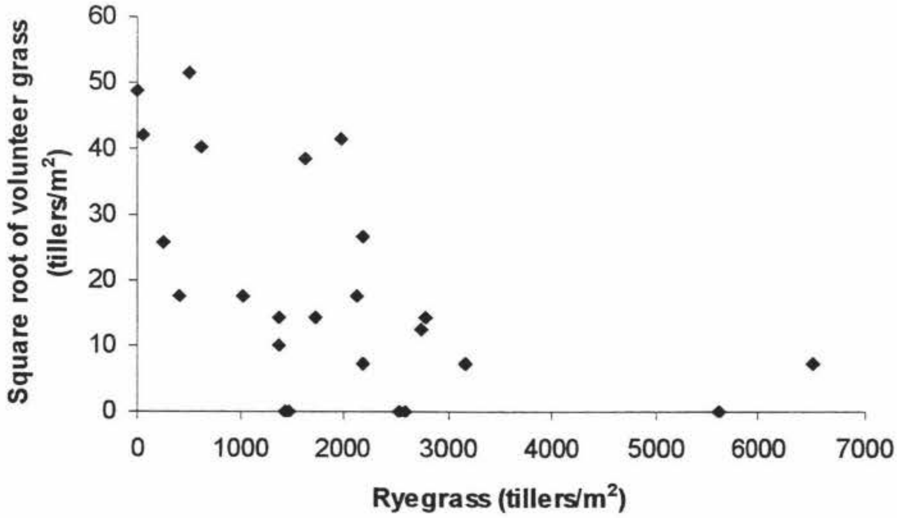

Figure 4.8. The relationship between ryegrass tiller density and volunteer grass density (12 months after pasture sowing), in the field experiment.

There was a significant negative ($P<0.001$) correlation between ryegrass tiller density and volunteer grass tiller density. This is an exponential relationship and accounts for 49.5% of the variation in the data (Fig. 4.8). Volunteer grass tiller density was square root transformed prior to this analysis.

The linear regression of volunteer grass (including seedlings) density and ryegrass tiller density indicated that a significant ($P=0.001$) negative relationship was apparent (Fig. 4.9). This relationship accounted for 43.1% of the variation in the data. The volunteer grass data was square root transformed prior to the analysis.

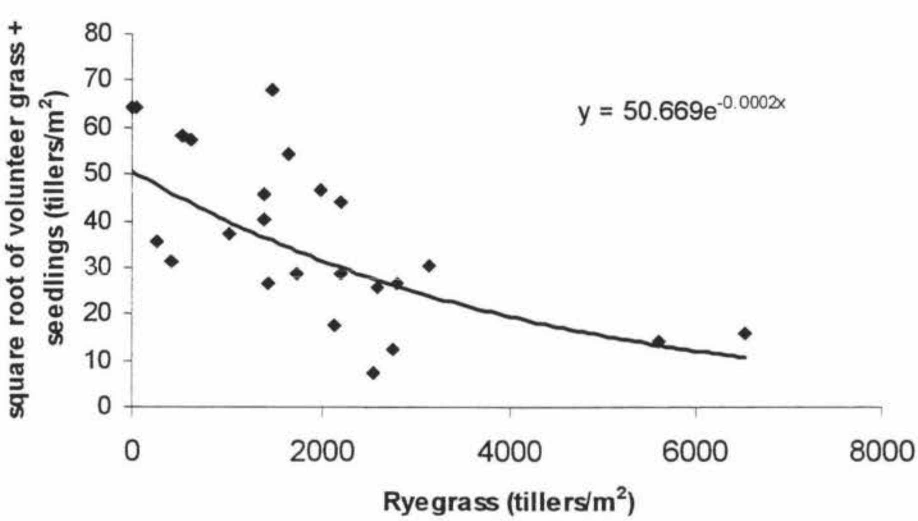

Figure 4.9. The relationship between ryegrass tiller density and the density of volunteer grass, including seedlings (12 months after pasture sowing), in the field experiment.

An analysis of variance on the total density of grass found no significant differences between the treatments (Fig. 4.10).

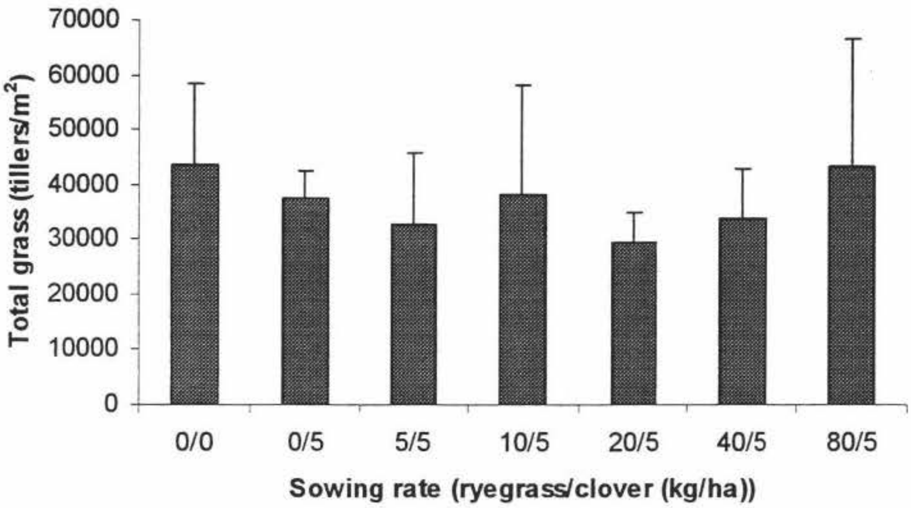

Figure 4.10. Effect of sowing rate on the total amount of grass (includes ryegrass, volunteer grass and grass seedlings) in the plots, 12 months after pasture sowing, in the field experiment (error bars indicate standard deviation).

4.3.2. Weed results.

In the field experiment, Treatment 1 refers to the treatment that originally was not sown with any pasture species. In the tray experiment, this equates to a "bare ground" treatment due to the continual removal of volunteer species. However, in the field experiment volunteer weeds were not removed to create a realistic pasture situation 12 months after the sowing of pasture species. For this reason, Treatment 1 in the field experiment was not a "bare ground" plot as volunteer weeds, grasses and legumes had established in the field plots.

Volunteer weeds and grasses were present in all of the field plots to a varying degree. They were more numerous in the plots with low ryegrass densities due to the decreased competition from perennial ryegrass (see Section 4.3.1). As was shown in this earlier section of the field results, the other components of the sward were all related to the ryegrass tiller density, and so very little would have been gained by analysing volunteer species against the results of the sown weeds.

4.3.2.1. Weed emergence.

This section on emergence relates to the total number of sown weed seedlings that emerged throughout the tray experiment. It does not take into account whether the seedlings survived or died. Mortality will be dealt with in a later section.

Scotch thistle – The highest emergence recorded in the field experiment was 37.2%, which equated to 93 seedlings emerging in one plot out of the 250 seeds sown. This maximum value is higher than the germination percentages found in the germination tests (Table 3.2), but lower than that recorded in the tray experiment (Chapter 3).

An analysis of variance indicated that the numbers of Scotch thistle seedlings emerging in Treatment 1 in the field experiment was significantly ($p<0.05$) less than that emerging in any of the other plots (Fig. 4.11). With Treatment 1 (0/0) removed there were no significant differences or trends within the sown treatments (i.e. Treatments 2-7).

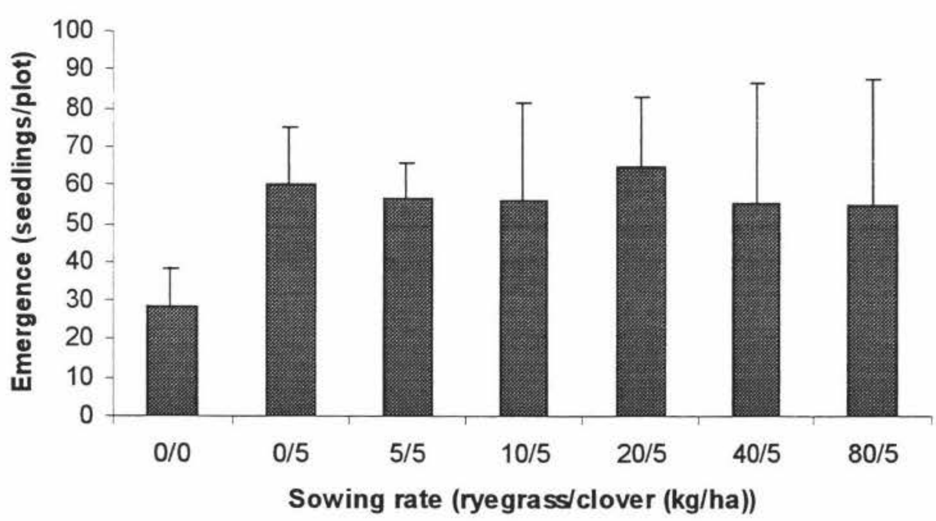

Figure 4.11. Effect of pasture sowing rates on mean Scotch thistle emergence (over 32 weeks) in the field plots, from the 250 sown seed (error bars indicated standard deviation).

A linear regression was performed on Scotch thistle emergence data using ryegrass tiller counts. A significant negative correlation ($P<0.05$, $r^2=0.183$) was found (Fig. 4.12).

When the treatments sown with ryegrass (i.e. Treatments 3-7) were analysed separately a significant negative correlation was still apparent ($P<0.05$, $r^2=0.207$).

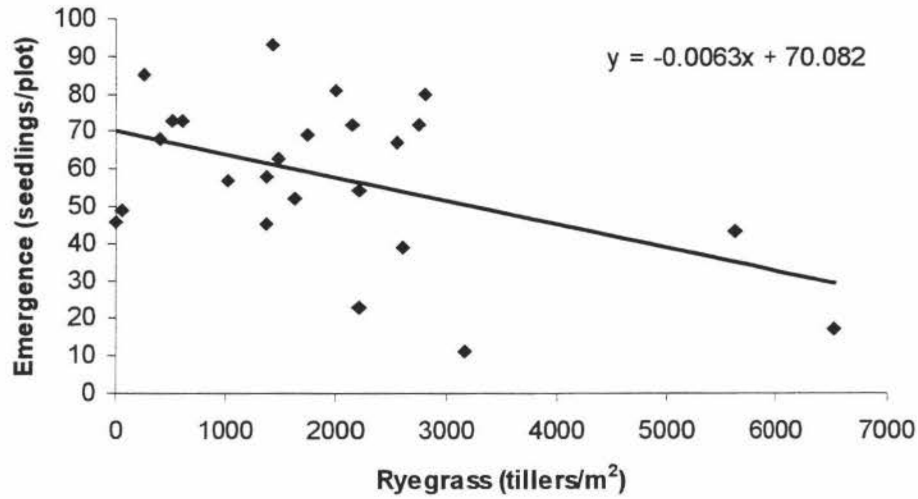

Figure 4.12. The relationship between Scotch thistle emergence per field plot and ryegrass tiller density.

Ragwort – The maximum emergence in a field plot was 77 seedlings out of the 500 seeds sown (15.4%). Again this result is higher than that recorded in the germination tests (Table 3.2), but lower than the maximum emergence recorded in the tray experiment.

Treatment 1 (0/0) had very similar ragwort emergence to that of the other low ryegrass treatments (Fig. 4.13). An analysis of variance indicated that there was a significant treatment effect ($P<0.05$) in the emergence data, however this probably relates to the differences between the three treatments with the highest ryegrass sowing rates (Treatments 5-7) and the others. The analysis of variance also indicated a significant ($P<0.001$) linear trend for increasing ragwort emergence as the ryegrass sowing rate increased.

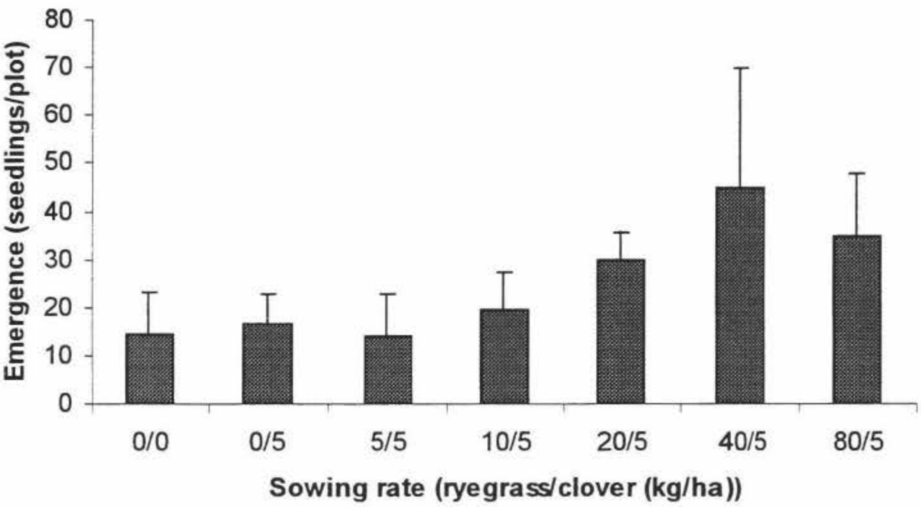

Figure 4.13. Effect of pasture sowing rates on mean ragwort emergence (over 32 weeks) in field plots (error bars indicate standard deviation).

A linear regression was performed on ragwort emergence and the ryegrass tiller density. When all of the data was included no significant trend was apparent. However, removal of an outlier (77 seedlings, 1019 tillers/m^2) gave a statistically significant trend ($P<0.05$) which accounted for 22.8% of the variation in the data (Fig. 4.14). It could also be argued that the two data points with the highest tiller density (47 seedlings, 5602 tillers/m^2 and 21 seedlings, 6518 tillers/m^2) were also outliers and have a large effect on the relationship; therefore these were also removed to examine the trend without the influence of these high points. Without the three "outliers" the trend became more significant ($P<0.01$) and 37.9% of the variation in the data was accounted for.

When the treatments that were originally sown with ryegrass (i.e. Treatments 3-7) were analysed separately and all of the "outliers" were included, there was no significant relationship apparent. However, with the data point 77 seedlings, 1019 tillers/m^2 removed a significant linear trend was obvious ($P<0.05$, $r^2=0.195$). As with the previous data set, the additional removal of the two high ryegrass tiller data points (47 seedlings, 5602 tillers/m^2 and 21 seedlings, 6518 tillers/m^2) increased both the significance of the relationship ($P<0.01$) and the variability that is accounted for by the regression (r^2 value becomes 0.433).

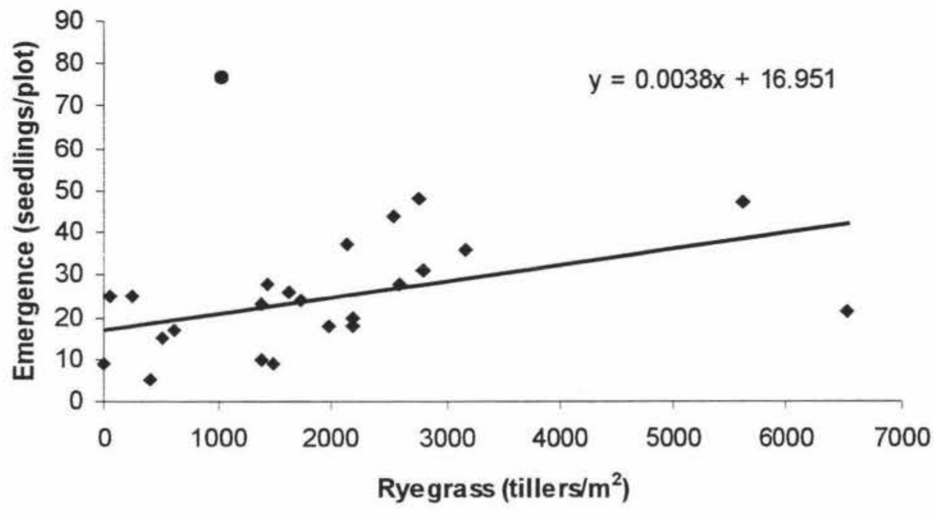

Figure 4.14. The relationship between ragwort emergence per field plot and ryegrass tiller density (outlier marked with "•"). The trend line is drawn without the influence of the outlier.

Hedge mustard – There was very little hedge mustard emergence in the field experiment, with mean values across the treatments of less than two seedlings emerging per plot (Table 4.2). The three treatments with the lowest sowing rates had no hedge mustard emergence whatsoever. The highest emergence per plot was 3 seedlings out of the 500 seeds sown or 0.6% germination. This value is extremely low when compared to the 70% germination recorded in the laboratory germination test (Table 3.2).

Table 4.2. Effect of pasture sowing rates on mean hedge mustard emergence in field experiment (over 32 weeks), from the 500 seeds sown.

	Sowing rate (ryegrass/clover (kg/ha))						
	0/0	0/5	5/5	10/5	20/5	40/5	80/5
Emergence	0	0	0	0.75	1.25	1.5	0.25

There was no significant effect of ryegrass tiller density on hedge mustard emergence in the field experiment (Fig. 4.15). When the treatments sown with ryegrass (Treatments 3-7) were analysed separately there was still no significant correlation between the variables.

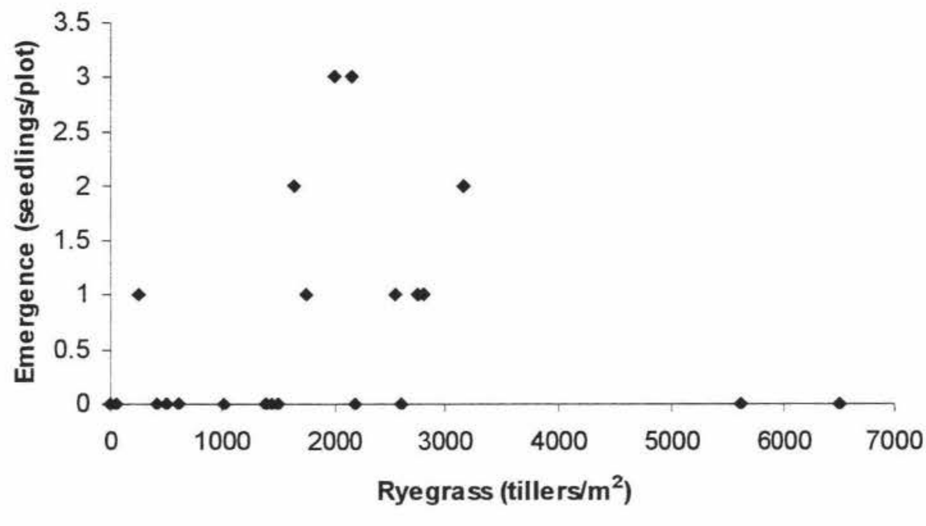

Figure 4.15. The relationship between hedge mustard emergence in the field experiment and ryegrass tiller density.

Nodding thistle – The highest nodding thistle emergence in the field plots was 13 seedlings out of the 500 seeds sown (2.6%). This value is lower than the values recorded in both germination tests, and also the tray experiment.

Although there was only a low number of nodding thistle seedlings emerging in the field plots, the numbers were greater than that for hedge mustard. The analysis of variance comparing nodding thistle emergence in the field experiment with the pasture sowing rate indicated that there were significant differences ($P<0.01$) within the emergence data (Fig. 4.16). With Treatment 1 (0/0) removed from the analysis a trend for nodding thistle emergence to increase as sowing rate increased was apparent. The emergence data underwent a square root transformation prior to these analyses.

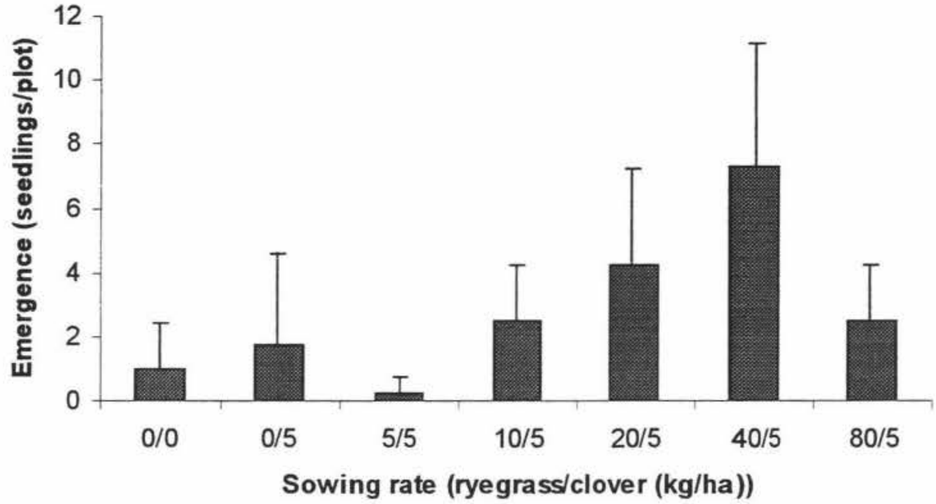

Figure 4.16. Effect of pasture sowing rates on the mean nodding thistle emergence (over 32 weeks) in the field experiment.

Total nodding thistle emergence increased significantly as ryegrass tiller density increased ($P<0.05$) (Fig. 4.17). However, only 8.7% of the variation in the data was accounted for by this relationship. Prior to this analysis the emergence data underwent a square root transformation.

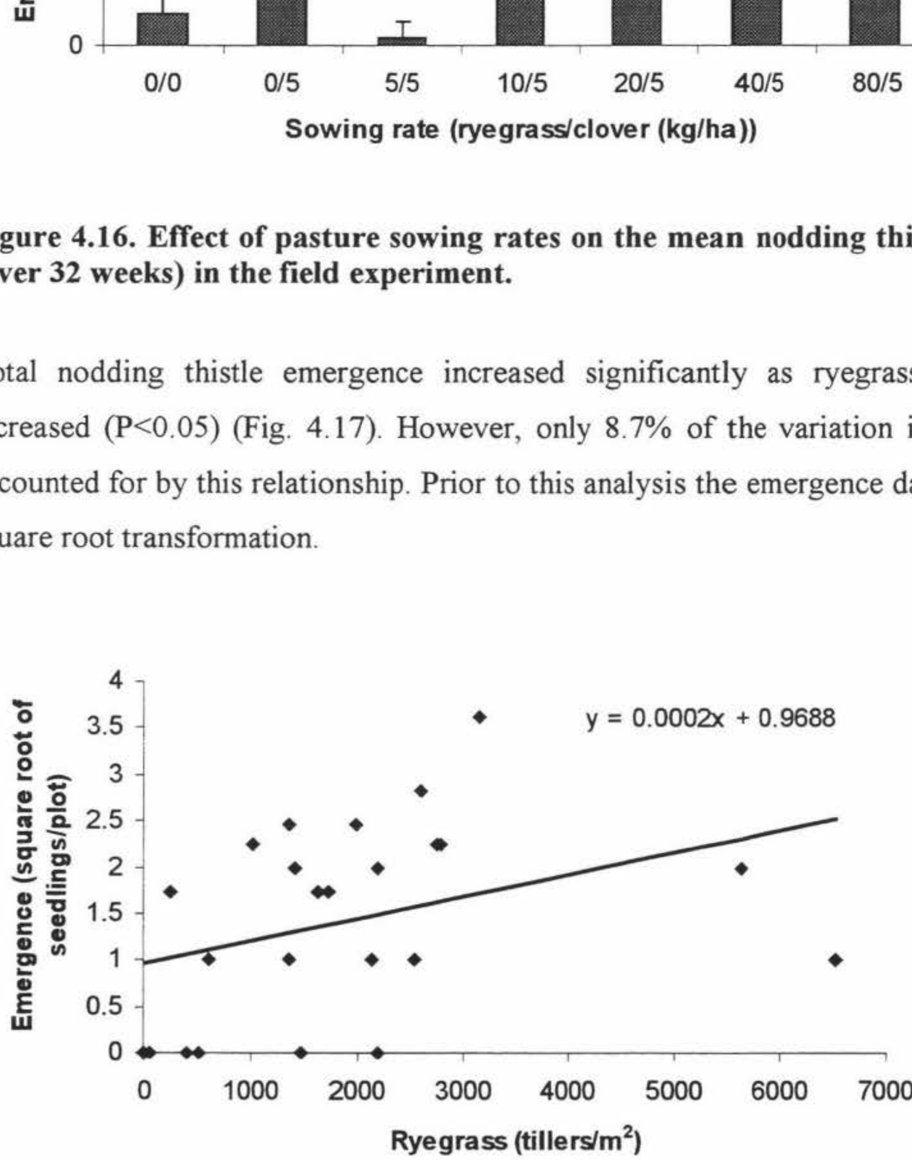

Figure 4.17. The relationship between nodding thistle emergence and ryegrass tiller density, in the field experiment.

4.3.2.2. Timing of emergence.

This section investigates the effect of ryegrass tiller density on the timing of weed emergence in the field experiment. Regression analyses were performed on the percentage of the total emergence that had occurred either at the first count (2 weeks after sowing) or the second count (6 weeks after sowing) depending on emergence rates. The experiment continued for 32 weeks for all weed species, so these counts indicate whether weed seedling emergence occurred earlier in plots with high ryegrass density or those with low ryegrass density. The timing of emergence data does not account for mortality, but simply measures the percentage of the total seedlings that emerged by the particular count. Treatment 1 (0/0) was not included in these regression analyses as this treatment is not a logical part of the progression of increasing ryegrass density.

Scotch thistle - A linear regression indicated a significant trend for Scotch thistle emergence to be delayed as ryegrass tiller density increased ($P<0.01$), accounting for 24.3% of the variability in the data (Fig. 4.18). When the two data points with the highest ryegrass tiller counts (5602 tillers, 27.9% emergence and 6519 tillers, 47.1% emergence) were removed then the relationship was still significant ($P<0.05$) and accounted for 24.7% of the variability in the data set.

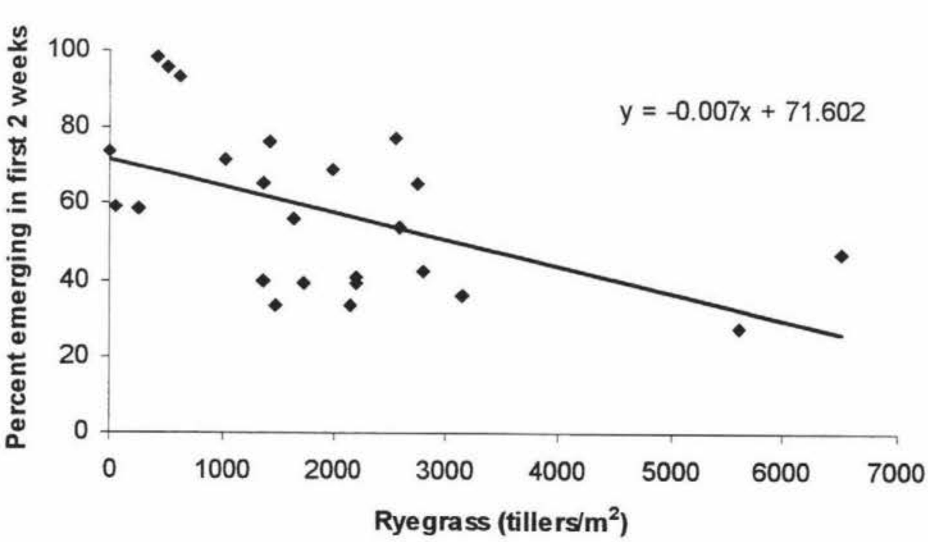

Figure 4.18. The relationship between the percentage of the total Scotch thistle seedlings that had emerged within two weeks of sowing and ryegrass tiller density.

In Treatment 1, 43.4% of the total Scotch thistle emergence occurred in the first two weeks after sowing the seeds.

Ragwort - With all data points included there was a significant linear trend ($P<0.05$) for a delay in ragwort emergence as ryegrass density increased, although only 14% of the variation in the data was accounted for by the relationship (Fig. 4.19). With the data point 21%, 2139 tillers/m^2 removed, $P<0.05$ and $r^2=0.222$ and with all three "outliers" removed (21%, 2139 tillers/m^2; 68%, 5602 tillers/m^2 and 57%, 6518 tillers/m^2) $P<0.05$ and $r^2=0.255$.

52.7% of the seedlings in Treatment 1 (0/0) emerged in the first 6 weeks of the experiment.

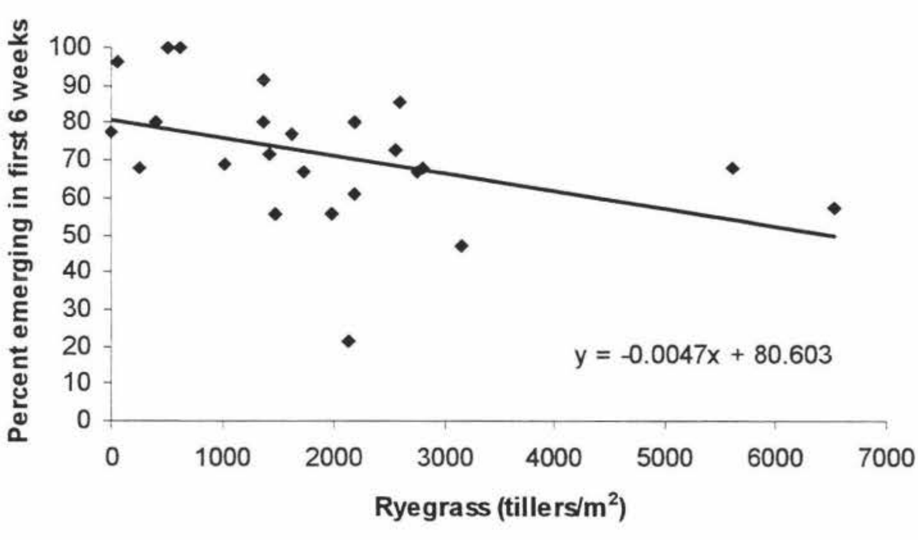

Figure 4.19. The relationship between the percentage of the total ragwort seedlings that had emerged within 6 weeks of sowing and ryegrass tiller density.

Hedge mustard - Nineteen of the twenty-eight plots in the field experiment had no hedge mustard emergence at all in the course of the experiment. Therefore, there was insufficient data to complete an analysis on timing of emergence.

Nodding thistle - Likewise, the low emergence of nodding thistle seedlings in the field experiment rendered the seedling count data meaningless and so no analysis was carried out.

4.3.2.3. Mortality

The majority of weed seedlings that emerged in the field experiment died before the end of the experiment, 32 weeks after sowing (Table 4.3). Only one nodding thistle seedling and no hedge mustard seedlings survived to the end of the experiment. For both Scotch thistle and ragwort there were no seedling survivors in either Treatment 1 (0/0) or Treatment 2 (0/5). The lowest mortality for ragwort was in Treatment 6 (40/5) with 79% of the emerging seedlings dying. Scotch thistle mortality was lowest in Treatment 7 (80/5) with 89% of the emerging seedlings dying before the end of the experiment.

TABLE 4.3. Effect of treatment (pasture sowing rates) on the mean number of weed seedlings dying throughout tray experiment. Percentage mortality figures are in brackets.

Treatment	Scotch thistle	Ragwort	Hedge mustard	Nodding thistle
1 (0/0)	28.5 (100%)	14.5 (100%)	-	1.0 (100%)
2 (0/5)	60.0 (100%)	16.8 (100%)	-	1.8 (100%)
3 (5/5)	55.8 (99%)	13.5 (96%)	-	0.3 (100%)
4 (10/5)	55.5 (99%)	17.8 (87%)	0.8 (100%)	2.5 (100%)
5 (20/5)	63.8 (98%)	28.3 (94%)	1.3 (100%)	4.3 (100%)
6 (40/5)	54.0 (92%)	35.0 (79%)	1.5 (100%)	7.0 (97%)
7 (80/5)	52.3 (89%)	27.5 (81%)	0.3 (100%)	2.5 (100%)

Arguably the best indicator of a sward's ability to resist weed invasion is the number of weed seedlings present at the end of the experiment. This measure incorporates both seedling emergence and survival.

Scotch thistle - The large number of zeros present in the Scotch thistle survival data made a binomial regression necessary. A significant ($P<0.001$) exponential regression was found (Fig. 4.20), indicating that Scotch thistle survival increased with increasing ryegrass density.

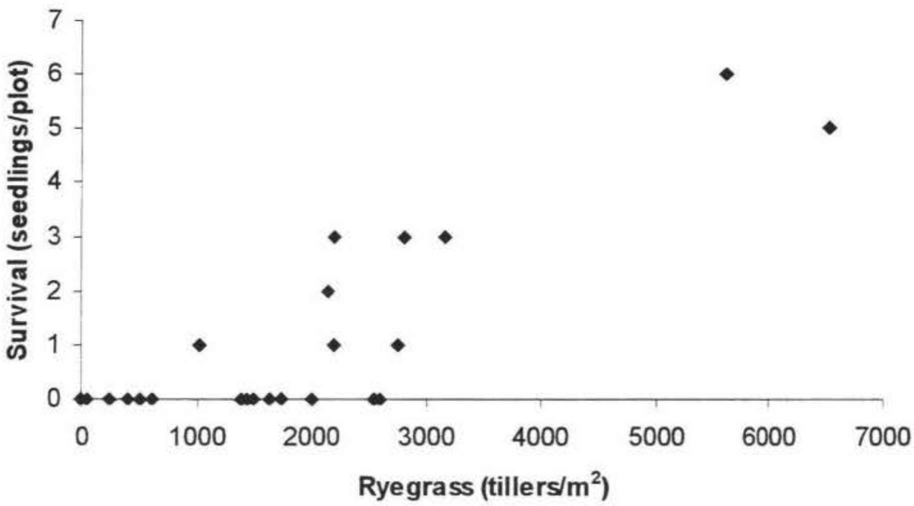

Figure 4.20. The relationship between the number of Scotch thistle seedlings surviving to the end of the experiment (32 weeks after sowing) and ryegrass tiller density.

Ragwort - The maximum number of ragwort seedlings alive in any one plot at the end of the experiment was 26, and these were found in Treatment 7. The linear regression analysis on the number of ragwort seedlings surviving until the end of the field experiment indicated a significant ($P<0.01$) positive correlation between survival and ryegrass tiller density (Fig. 4.21). The data indicating the number of plants surviving required a square root transformation prior to the analysis.

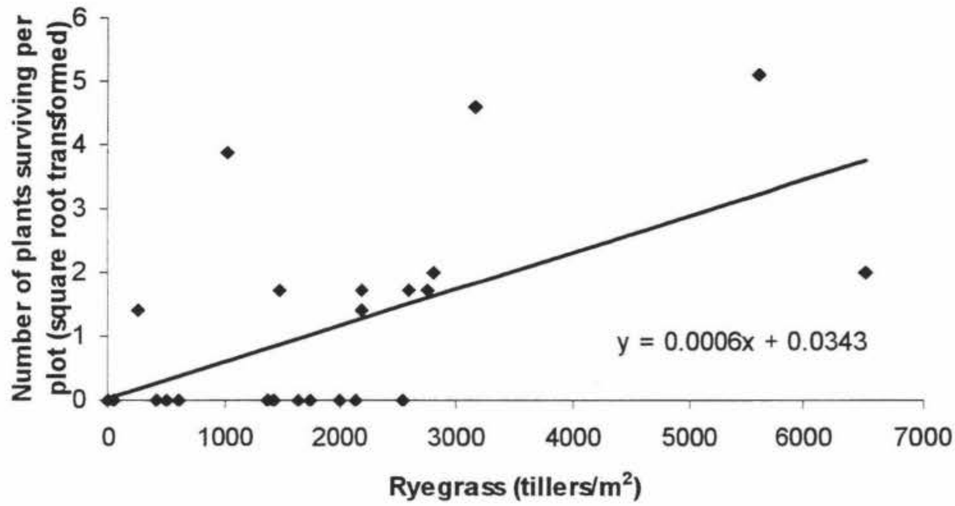

Figure 4.21. The relationship between the number of ragwort seedlings surviving (square root transformed) to the end of the experiment (32 weeks after sowing) and ryegrass tiller density.

Hedge mustard - All of the hedge mustard seedlings that emerged during the experiment died; therefore no regression analysis could be carried out.

Nodding thistle - Only one nodding thistle seedling survived to the end of the experiment over all the field plots, so again no regression analysis could be carried out on surviving plants.

4.4. Discussion of field experiment

4.4.1. Pasture condition when weed seeds sown

The pasture composition data from the field experiment was more variable than for the tray experiment. This was to be expected since there is much more inherent variability in a field situation. A major difference between the two experiments was that volunteer weeds were removed from the trays but not from the field plots. Weeding was decided against in the field experiment to enable a realistic pasture situation to develop as broad-leaved weeds and volunteer grasses are a fact of life in newly sown pasture. The presence of these volunteer species would have increased the overall plant density in the lower sowing rate plots and subsequently introduced more competition for the emerging seedlings in the experiment. It is important to note that Treatment 1 was originally not sown with any pasture species (as in the tray experiment). However, in the field experiment Treatment 1 can not be considered a "bare ground" plot due to the presence of broad-leaved weeds and volunteer grasses. Another factor increasing variation in the field plots was the effects on the pasture of livestock, i.e. treading damage, cow pats, uneven grazing heights and the random introduction of high levels of nitrogen (urine spots).

Measurements of pasture composition were made 12 months after the pasture species were sown. The relationship between ryegrass sowing rate and ryegrass tiller counts at this time in the field plots was very similar to that seen in the trays (Fig. 4.1). However, there was more variation in the field data, for the reasons stated above, and so there was overlap of tiller density values between the different sowing rates. There was a suggestion that the relationship was asymptotic however this was not as pronounced with the field data compared to the tray data due to the lower range of sowing rates in the field. It must be remembered that the pasture composition measurement provide only a "snapshot in time" of what the field plots looked like when the weed seeds were sown. The pasture composition measurements were not repeated and so by the end of the experiment the field plots could have looked very different from what the pasture composition section would suggest. However, the relative differences between the treatments are likely to be similar i.e. Treatments 1 and 2 would still have a much larger broad-leaved weed population than Treatment 7.

One point to note is that the tiller densities recorded in the field plots are not necessarily as high as would be expected in a typical dairy pasture. However, it must be remembered that the tiller density measurements were taken in mid-autumn (i.e. April), and that tiller numbers vary throughout the year, reaching a peak in late September and then decreasing to the lowest density by the end of Feburary (Smetham 1990). Tiller density measurements given by L'Huillier (1987) for April range from about 3,200 tillers/m^2 to 5,300 tillers/m^2 depending on the stocking rate (the higher value refers to a higher stocking rate). By comparison mean grass densities recorded in this experiment in the field were about 4,500 tillers/m^2 (value includes perennial ryegrass, volunteer grass and grass seedlings (Fig. 4.10)) so it would seem that the densities achieved in this experiment are not too different to what is expected for that time of year. However, if only perennial ryegrass densities are taken into account then the average tiller density would be much lower as the majority of the field plots had densities below 3,000 tillers/m^2 (Fig. 4.1). The tiller densities in this experiment could have been higher if the grazing had been harder. The rather lax grazing that occurred during the experimental period enabled the sward to attain extra height before being grazed. This would have caused more self-thinning to occur due to the limited amount of biomass that an environment can maintain, therefore lower ryegrass tiller densities would have resulted.

Another point to note with the pasture composition measurements is that these results give an estimate only of the sward composition and as such there is no indication as to the variation within the plots. For example, one plot could have a dense clump of ryegrass and a large amount of bare ground whereas another might have evenly spaced ryegrass tillers. In this situation both plots could potentially have the same tiller counts and thus be considered the same. In reality, however, these scenarios would have very different effects on an establishing weed population.

There was some suggestion of a decrease in white clover growing points as ryegrass sowing rates increased (Fig. 4.2), however this was not a significant trend. White clover density in the two highest sowing rates was much lower than in the lower sowing rates indicating that the white clover is seriously out–competed once more than 40 kg/ha of ryegrass seed is sown.

There was also no significant relationship between ryegrass tiller density in the field plots and the density of white clover (Fig. 4.3) whereas in the tray experiment ryegrass tiller density had a significant effect on white clover density. This result from the field indicates that competition from other species (i.e. broad-leaved weeds and volunteer grasses) may have affected white clover density especially in the lower sowing rates. This would explain why there was little difference in clover density between treatments in the field plots yet significant declines in clover density were found in the tray experiment with increasing sowing rates and tiller densities when these additional species were not present.

A previous experiment by Cullen (1964) indicated that clover is not necessarily out-competed by perennial ryegrass long-term as predicted. He discovered that in the early establishment period clover was suppressed in proportion to the ryegrass seeding rate, however, in the second year clover growth was superior in the high density ryegrass treatments. This was assumed to be related to a deficiency in nitrogen in the high density ryegrass plots with a consequent decline in grass vigour, allowing the white clover to grow unchecked. His results at the end of the two year period indicated that clover yields were thus ultimately greatest in those treatments where the suppression effects of ryegrass were initially most noticeable. However, over the two year period, total clover yields did not vary greatly among his treatments due to the earlier suppression effects in the high ryegrass treatments.

An interesting point to note from the white clover in the field plots is that Treatment 1 (which was not originally sown with any white clover seed) ended up with the highest numbers of white clover growing points out of all the treatments. This can be explained by recruitment of white clover from the seedbank. The lack of sown pasture species in this treatment would have presented any emerging seedlings from the seedbank with no competition thus enabling them to establish successfully.

The relationship between sowing rate and broad-leaved weed density indicated that there were significantly more broad-leaved weeds present in the plots with a sowing rate of less than 10kg/ha ryegrass (Fig. 4.4). This suggests that once 10kg/ha or more of ryegrass seed is used during pasture establishment the resulting ryegrass population will significantly reduce, through competition, the amount of weeds present in the plots 12 months later. The results from the previous year's experiment on the same site indicated that as perennial ryegrass sowing density increased, the weight of sown weeds that were present decreased in a linear manner (Seefeldt & Armstrong 2000). In this earlier experiment both the weed seeds and the pasture species were sown at the same time and measurements were taken both 6 weeks and 9 months after sowing. At the time of the earliest measurement, the process of self-thinning probably had not begun as the pasture would not have been fully established. Consequently the sown treatments would have had varying amounts of biomass and competitive pressure would have increased as sowing rate increased. In this current study, it appears that competitive pressure was similar between plots with ryegrass sowing rates above 10 kg/ha due to the process of self-thinning. At sowing rates above 10 kg/ha of perennial ryegrass, any further increase in sowing rate apparently had no added benefit in reducing the weed biomass present in the plots.

As ryegrass sowing rate and ryegrass tiller density increased, the amount of volunteer grass present in the plots decreased (Fig. 4.6 & 4.8). Once again this indicates that as ryegrass density increased, the competitive pressure exerted on the volunteer grasses also increased, resulting in fewer volunteer grasses establishing in the high ryegrass density plots and those that did establish remaining small in size. The majority of the tillers falling into the category of volunteer grass were from either annual poa (*Poa annua*) or browntop (*Agrostis capillaris*) plants. When grass seedlings are included in the counts of volunteer grass, a similar trend to that found with the adult volunteer grass data is apparent (Fig. 4.7). Although there is no guarantee that the grass seedlings would have established successfully, the likelihood of establishment is higher in plots with a large number of grass seedlings than in plots without any seedlings. Presumably if there was sufficient space and light to encourage germination and emergence of the grass seedlings, then establishment should be successful for many of the seedlings.

Interestingly when the total amount of grass (i.e. ryegrass, volunteer grass and grass seedlings) present in each plot is examined there is no significant difference between the treatments (Fig. 4.10). However, although the density of grass is similar in all of the field plots, the type of grass varies and thus the ability of the sward to resist weed invasion is dependent on the competitive ability of the dominant species. This factor could be particularly important when considering a plot that has a high density of perennial ryegrass versus one with a high density of annual poa. As the name suggests, annual poa completes its life cycle within one year. This grass therefore has a cyclical nature and usually dies back within a year. In contrast, perennial ryegrass grows throughout the year and thus remains a competitive force at all times.

4.4.2. Weed results

The maximum emergence percentages in the field experiment were low. Over all of the species, the maximum emergence was 37.2% of the sown seeds, which was recorded for Scotch thistle. The maximum emergence per plot was 15.4% for ragwort and less than

3% for both nodding thistle and hedge mustard. Although these emergence values are low, the data from the tray experiment (for ragwort and Scotch thistle) and the germination tests (for hedge mustard) indicate that the weed seed has more viability than is suggested by the field experiment. However, the nodding thistle seed had indicated low viability in the germination tests, tray and field experiments therefore indicating that the low emergence values were mainly due to poor viability of the seed rather than effects of the treatments.

4.4.2.1. Scotch thistle

Total Scotch thistle emergence in Treatment 1 was significantly less than in the other treatments (Fig. 4.11). The timing of this emergence was also slower than all the other treatments with the exception of Treatment 5 (20/5) (Fig. 4.18). It must be remembered that in the field experiment Treatment 1 was not a "bare ground" plot due to the presence of broad-leaved weeds and volunteer grasses and so throughout the experiment there was a large amount of volunteer species present in these plots. Although Treatment 1 had no perennial ryegrass present, these plots had the highest density of volunteer grasses, and surprisingly when ryegrass tillers are also included, Treatment 1 actually has the highest mean density of grass out of all of the treatments. Treatment 1 also had the highest density of white clover out of all the treatments. These factors gave Treatment 1 a high plant density resulting in low light levels and few potential germination sites and therefore Scotch thistle emergence was both reduced and delayed in this treatment.

Studies by both Grime *et al.* (1981) and Doucet & Cavers (1996) have indicated that Scotch thistle seed can acquire a light requirement for germination if the seed experiences a period of darkness, or the red/far red ratio is below about 0.5 once it has imbibed (Grime *et al.* 1981). In the current field experiment this induced dormancy could have prevented the Scotch thistle seed from germinating when located in deep shade. It could be argued that seeds in Treatment 1 were more likely to experience deep shade due to the large amount of volunteer grass, white clover and broad-leaved weeds in these plots (due to the lack of competition from ryegrass), whereas Scotch thistle seeds in the treatments sown with ryegrass could potentially have experienced more light due to the lower overall plant density in these plots. These factors could help to explain why emergence was low and delayed in Treatment 1 compared to the other treatments.

As with the tray experiment, once Treatment 1 is removed from the analysis, the number of Scotch thistle seedlings emerging decreased as ryegrass tiller density in the field increased (Fig. 4.12). This result could be related to the presence and size of gaps in the sward. In the field plots that were sown with high seeding rates of ryegrass, the plots would have a more uniform sward as it would predominantly be made up of ryegrass plants that all established at the same time. As the seeding rates decrease the plots would become progressively more varied with increased amounts of white clover and also broad-leaved weeds and volunteer grasses. The presence of large leaved weeds in the plots with low ryegrass densities would have led to a reduction in plant density, as there is a maximum amount of leaf area that any environment can maintain. A large leaved weed would intercept much of the incoming light making it difficult for shaded plants to maintain a positive carbon balance and so thinning would occur. Therefore these more varied plots would have had a higher incidence of gaps in the pasture and thus more germination sites would be available, leading to increased Scotch thistle emergence in the low density ryegrass plots. A study by Panetta & Wardle (1992) has indicated that emergence of Scotch thistle was significantly higher in gaps with 2 cm diameter than was recorded in swards with no gaps or bare ground.

Among Treatments 2-7 there was a significant trend for Scotch thistle emergence to be delayed as ryegrass density increased (Fig 4.18). The data for the timing of Scotch thistle emergence was recorded two weeks after the weed seeds were sown. Prior to sowing the Scotch thistle seeds the plots were trimmed to 3cm height to ensure that the seed reached the surface of the soil within the plot. The effect of this trim would have been to allow light to penetrate the sward in all treatments. This would especially have affected the low density ryegrass plots with large-leaved weeds as these leaves would have been removed by the trimming. So, in this case the high density ryegrass plots may have had lower light levels at the beginning of the experiment, due to the large number of stems present. This could help to explain why there was a significant trend for Scotch thistle emergence to be delayed as perennial ryegrass density increased. This trend may also be related to available germination sites. As was mentioned earlier there may be more germination sites available in the lower ryegrass density plots and therefore germination could have occurred earlier in these plots for this reason.

As the number of perennial ryegrass tillers increased, the number of Scotch thistle seedlings surviving until the end of the experiment also increased (Fig. 4.20). This trend could be explained by the physical protection from grazing animals afforded by the high density ryegrass swards. This result was the opposite of what was found for Scotch thistle in the tray experiment where the number of plants alive at the end of the experiment decreased as ryegrass density increased. However, in the trays survival was very closely related to emergence due to low mortality whereas in the field mortality was high due to damage from grazing animals and high density ryegrass swards offered more protection and therefore these plots had more survivors.

4.4.2.2. Nodding thistle

There was very low nodding thistle emergence in the field plots. However, as ryegrass sowing rate (Fig. 4.16) and ryegrass tiller density (Fig. 4.17) increased the number of nodding thistles emerging in the field plots increased. An experiment by Medd & Lovett (1978) indicated that nodding thistle seed exhibits a phytochrome response and thus requires light for germination. As mentioned earlier, the presence of large-leaved weeds in the low ryegrass density field plots of this current study could have resulted in lower light levels reaching the soil surface, therefore reducing the total emergence in these plots. The low emergence values in the field experiment show a similar result to that found in the tray experiment and the germination tests, thus indicating that the nodding thistle seed used in these experiments had a low viability. However, the emergence results under the established swards in both the field and tray experiment were both lower than the laboratory germination tests, indicating that nodding thistle has difficulty in emerging in an established sward. This is further enhanced by the fact that only one nodding thistle survived to the end of the field experiment.

4.4.2.3. Ragwort

There was a significant linear trend for ragwort emergence to increase as the ryegrass sowing rate increased (Fig. 4.13). Broad-leaved weeds and volunteer grasses were not removed from the field plots during the course of this experiment. Consequently, 12 months after the pasture species were sown (when the weed seeds were introduced) the amount of broad-leaved weeds, volunteer grasses and white clover varied widely due to competition (or lack of it) from ryegrass. These species all contributed to the overall plant density of the plots and the positive trend for ragwort emergence to increase as sowing rate increases may in fact indicate that some of these volunteer species are more competitive against ragwort than is perennial ryegrass (Armstrong *et al.* 2001). Another factor to consider is that (as postulated in the tray experiment) the size of the perennial ryegrass tillers may have been larger in the plots with low perennial ryegrass density due to the lower amount of intra-specific competition they were subject to. Therefore, the plots with low perennial ryegrass density may have exerted more competitive pressure than the ryegrass tiller density measurements suggest. Harper & Wood (1957) have also suggested that white clover may be more competitive against ragwort than grasses due to a similar growth form. This result is similar to that found in the tray experiment where ragwort emergence also increased as ryegrass density increased. In that experiment it also seemed likely that the competitive pressure experienced by the ragwort was similar in all trays due to infill by white clover, and differing ryegrass tiller sizes.

With an outlier removed, increases in ryegrass tiller density also resulted in an increase in ragwort emergence (Fig. 4.14). This relationship is not significant when all data points are included. This indicates that the relationship was not particularly strong and in reality it would be more likely that ragwort emergence was not affected by ryegrass density. This result strengthens the suggestion that the increase in ragwort emergence as the ryegrass sowing rates increased is actually due to either the competitive effects of the other species present in the sward, or that due to the larger sized tillers in the low ryegrass density plots, there was a similar amount of competitive pressure in all treatments.

There was a trend for ragwort emergence to be delayed as ryegrass tiller density increased (Fig. 4.19). This result was again similar to that found in the tray experiment. This result may relate to the number of germination sites available in each treatment. As postulated earlier in the tray experiment, the lower light levels present over the winter months would have caused thinning to occur in all of the field plots. Presumably, at the beginning of the experiment there would have been fewer germination sites present in the high ryegrass density treatments due to the dense swards of ryegrass that all established at the same time. In contrast the low ryegrass density plots had more varied vegetation including large-leaved weeds that (as explained earlier) would have resulted in a decreased overall plant density in the plots. Therefore germination could have occurred earlier in the low density ryegrass plots due to the ready availability of germination sites. By comparison, in the high density ryegrass plots emergence could have occurred later as self-thinning with the lower light levels over winter would have opened up the vegetation and thus enabled more germination to occur.

4.4.2.4. Hedge mustard

There was very little hedge mustard emergence in the field plots (less than 2 seedlings per plot) (Table 4.2). Hedge mustard seed is absolutely dependent on light for the onset of germination (Bouwmeester & Karssen 1989). The results from this field experiment suggest that the presence of vegetation, irrespective of sward composition or ryegrass density, will prevent enough light from reaching the soil surface to prevent hedge mustard germination.

The hedge mustard result is very similar to the results from the tray experiment. It would appear from both experiments that hedge mustard emergence is almost completely prevented by the presence of an established sward. The composition of the sward does not appear to be important as all treatments with vegetation appeared to reduce hedge mustard emergence to negligible amounts. The only treatment that had any emergence of note was Treatment 1 in the tray experiment. This was also the only treatment in either experiment to have no vegetation present.

4.4.3. Summary

In no field plots did weed emergence decrease with an increase in ryegrass sowing rate. Very low emergence was recorded with both nodding thistle and hedge mustard in the field plots. For nodding thistle the low emergence probably relates to the low viablility of the seed. However, for hedge mustard the presence of an established sward almost completely prevents emergence.

Mortality was much higher in the field experiment when compared to the tray experiment due to both the physical effects of grazing animals and also the longer time frame of the field experiment. Although once established, both ragwort and Scotch thistle tended to have an increased chance of survival in field plots which contained dense swards of perennial ryegrass. This presumably is due to the physical protection afforded by the ryegrass, from grazing animals. However, it is not known whether the few weed seedlings that survived to the end of field experiment would have grown to maturity due to the large amount of competition that they faced from the surrounding pasture.

CHAPTER FIVE

General Discussion

5.1. Pasture composition

The measurements of pasture composition were taken 8 months (for the tray experiment) or 12 months (for the field experiment) after the pasture species were sown. For both the trays and field plots, it appears that plant density at the time of this assessment was similar in all treatments due to infill in the low ryegrass density plots and self-thinning in the high ryegrass density plots. Swards with low densities of perennial ryegrass may also have had larger sized tillers than those present in the high density ryegrass swards due to the extra resources available. However, no measurements of tiller size were made.

In the tray experiment, the low ryegrass density plots had a much higher density of white clover (Fig. 3.2) due to lower competition from ryegrass. Therefore the strong growth of white clover would have added a significant amount to the overall plant density in the low ryegrass plots. In the high ryegrass sowing rate trays, self-thinning (or density dependent mortality) would have occurred in the ryegrass population therefore potentially resulting in an overall plant density similar to that of the low sowing rate plots. The different components that made up the overall plant density (i.e. white clover and perennial ryegrass) may however have had different effects on any emerging weeds.

In the field experiment the presence of broad-leaved weeds and volunteer grasses affected the overall plant density of the plots. The field plots with a low ryegrass sowing rate did not have significantly more white clover than the high ryegrass density plots. However, there were significantly more volunteer grasses (Fig. 4.6) and broad-leaved weeds (Fig.4.4) in these plots which would have increased competition against the white clover hence reducing its density. There were low levels of both white clover and volunteer species in the high ryegrass sowing rate plots due to competition from the ryegrass. Again the eventual plant density of all the field plots would have been similar due to infill by volunteer species at the low ryegrass densities, and self-thinning by ryegrass and the reduction of other species at the high ryegrass densities.

So, although the different pasture sowing rates would have resulted in a range of plant densities in the first few months after sowing, the processes of self-thinning and infill and the variable sizes of perennial ryegrass tillers would have evened out the overall competitive pressure exerted by the different treatments. However, each treatment would have been comprised of a different composition of plants and each component would potentially have a different competitive ability within the sward. The competitive effects that different species have on emerging weeds will vary throughout the year as different species have different peaks of growth. Also, annual species, such as annual poa, will eventually die potentially leaving a gap in the sward.

5.2. Weed results

In the trays Scotch thistle emergence decreased as ryegrass sowing rate increased (Fig. 3.8), however in the field plots emergence was unaffected by sowing rate (Fig. 4.11). The negative effect of increased sowing rate was even more pronounced with hedge mustard, where the presence of any vegetation reduced emergence to negligible levels (Fig. 3.12 and Table 4.2). Nodding thistle and ragwort however, had some unusual results. Both of these species experienced an increase in total emergence as ryegrass sowing rate increased. With nodding thistle this occurred in the field (Fig. 4.16) and with ragwort, in both the trays (Fig. 3.10) and the field (Fig. 4.13). This obviously was unexpected but in reality the increases, although significant were small and of little practical importance. However, these unusual results may indicate that the competitive pressure experienced by the emerging weed seedlings is not just a function of ryegrass tiller density. Nodding thistle emergence in the trays (Fig. 3.14) indicated no effect of ryegrass density on total emergence.

Weight per plant data was only collected from the tray experiment due to high mortality in the field experiment. In all cases the highest weights were found in Treatments 1 or 2 indicating that the presence of ryegrass had a serious negative effect on weed size (Figs. 3.16, 3.19, 3.22, 3.24). However, it tended not to be important how dense the ryegrass sward was as weed sizes did not vary significantly as ryegrass density increased. This again indicates that once established, swards with varying densities of ryegrass exert similar competitive pressure on weed seedlings.

With all species the timing of emergence was delayed as ryegrass density increased (Sections 3.3.3.3 and 4.3.2.2), suggesting that either the amount of light or the number of available germination sites decreased as ryegrass density increased. Delayed emergence could be either an advantage to the seedling or a disadvantage depending on the pasture conditions at the time of germination. Seeds that germinate immediately after being shed, in late summer or early autumn, run the risk of inadequate moisture to sustain life. However, if moisture is not limiting then seedlings that germinate early gain resource advantages over seedlings that germinate later. Therefore, it would seem that for a weed species to ensure that some seedlings survive to reproduce, having a range of germination times is desirable so that whenever optimum conditions are available, some seeds are ready to germinate.

Due to the low mortality in the trays (Table 3.4), the number of weed seedlings surviving to the end of the tray experiment was merely a function of the number emerging. However, mortality was much higher in the field due in part to the effects of grazing animals (Table 4.3). All of the hedge mustard seedlings that emerged in the field were killed, and only one nodding thistle survived to the end of the experiment. With both Scotch thistle and ragwort, seedlings seemed to have a higher chance of surviving in the high density ryegrass treatments (Fig. 4.20, 4.21), probably due to the physical protection from grazing animals provided by the ryegrass. Other reasons for the differences in mortality between the field and tray experiment are discussed in the next section (Section 5.3).

Overall, these results seem to indicate that of the four weeds studied, hedge mustard is the least likely to be a problem in pastures. This weed requires pasture gaps to germinate and therefore infestations can be avoided by maintaining a dense sward.

Hedge mustard is only likely to successfully invade pastures after a severe disturbance has opened up the sward i.e. drought or overgrazing.

From this experiment nodding thistle establishment also appears to be limited by a dense sward of ryegrass. This weed also appears to require pasture disturbance to establish successfully. This is highlighted by the fact that only one nodding thistle seedling survived in the field experiment. However, due to the low viability of the nodding thistle seed used in this experiment these results need to be treated with caution and not relied upon unless further experimentation can provide further evidence.

Out of the four weed species studied it would appear that ragwort and Scotch thistle were the weeds most suited to establishing in a dense sward. Both of these species had relatively high emergence and survival rates in both the field and tray experiments. However, even with these species Scotch thistle showed reduced and delayed emergence in both the trays and the field with increasing ryegrass density. The seedlings growing in the trays that contained no ryegrass were also consistently larger than in trays with ryegrass. In these experiments ragwort indicated an ability to emerge under high density ryegrass swards; however, again the size of the seedlings was reduced under a dense sward of ryegrass. Therefore, even with ragwort and Scotch thistle it appears that a dense sward that includes perennial ryegrass will help to reduce the invasion of these weeds.

5.3. Differences between field and tray experiment

There were some significant differences in the results obtained from the tray and field experiments. With all of the species studied weed emergence was significantly higher in the tray experiment when compared to the field experiment. The other major difference between the two experiments was the level of mortality throughout the experimental program. In the trays the highest mortality for all species was in Treatment 1 (with the exception of nodding thistle which had no emergence in this treatment), where up to 60% of the emerging seedlings died in the course of the experiment. However, the sown treatments are more directly comparable to the field experiment as all field plots contained vegetation. In the sown treatments, all species lost fewer than 5 seedlings per tray, which in most cases equated to less than 5% of the emerged seedlings. By comparison, the mortality in the field experiment was much higher. The lowest ragwort mortality in the field experiment was 79%, and for Scotch thistle was 89%. Hedge mustard had 100% mortality in all plots and nodding thistle had only one seedling surviving the duration of the experiment.

There were some major differences between the field and tray experiments which may have influenced the relative competitiveness of the swards and thus the results in these different sites. Significant points include the different lengths of time that the field and tray swards had to establish before the weed seeds were introduced, the different length of the experiments once the weed seeds were introduced and the differences in grazing intensity between the two sites.

The pasture in the tray experiment was sown 8 months before the weed seeds were introduced into the treatments. By comparison the swards in the field experiment had 12 months to establish, before the weeds were sown. These time differences may have had an influence on the competitive ability of the swards when the weeds were sown. Presumably, the swards in the trays would have had less time for the processes of self-thinning and infill to occur and so the competitive differences between the treatments may have been more marked than in the field experiment. These differences may have been further pronounced by the lack of volunteer species in the trays which, in the field, would have sped up the process of infill as there were more plants ready to fill any available space.

Once the weed seeds were sown, measurements for the tray experiment finished sooner (i.e. 15-20 weeks) than for the field experiment (32 weeks). This fact meant that the weed seedlings in the field experiment were subjected to competition from the pasture for a much longer time than those weed seedlings growing in the trays. This could have resulted in a larger number of weeds dying in the field due to the suppressive effects of the sward.

Another factor that would have influenced the competitiveness of the swards is the grazing intensity at the different sites. Throughout the duration of the field experiment, the plots were laxly grazed (i.e. on average every nine weeks). Subsequently the pasture plants in the field plots were allowed to grow to a large size before grazing occurred. This would have resulted in a highly competitive sward that would have filtered out a large amount of the available light before it reached the soil surface, making it very difficult for small weed seedlings to establish. By comparison, the trays were artificially grazed to a height of 3cm every 30 days, thus enabling light to penetrate the sward much more effectively.

The three factors mentioned above (i.e. time from pasture sowing to weed sowing, length of experiments, and grazing intensity) would have had a large effect on the relative competitiveness of the swards at the different sites, ensuring that weeds in the field plots had much more difficulty surviving. Therefore, the high mortality in the field experiment can be explained by both the physical effects of grazing animals and the greater amount of competition experienced.

5.4. Timing of experiments

The weed seeds were introduced into the field experiment in mid-autumn (18 May) and the tray experiment in late-autumn (18 June). Had the experiments been sown earlier there potentially could have been more weed emergence in the tray experiment due to the warmer temperatures that would have been experienced. This may also have been the case in the field experiment providing that moisture was not limiting. However, the longer that seeds remain in or on the soil without germinating, the higher the probability that the seed will be lost to either predation or fungi. Seeds that germinated earlier in the field i.e. late summer, would have been more prone to death through desiccation due to the less reliable rainfall at that time of year. The regular watering of the tray experiment would have ensured that any seedling that germinated had sufficient moisture to survive.

5.5. Overall Discussion

It would seem from earlier experiments that have examined the effect of different seeding rates on weed populations that high seeding rates put enormous competitive pressure on emerging weed seedlings and that subsequent populations are much reduced in the first year after the pasture is sown (Cullen & Meeklah 1959, Seefeldt & Armstrong 2000). However, results from this current experiment suggest that these advantages are not as pronounced in the second year. In many of the results it would appear that the presence of any amount of ryegrass was enough to out-compete emerging weed seedlings and that no real advantage was to be gained through the higher seeding rates. In some cases (i.e. ragwort) the emerging weeds even seemed to gain some advantage in the denser ryegrass swards. Presumably these small seedlings would have difficulty surviving in a dense sward though unless a pasture gap opened up above them.

One point to consider is that although when established the higher density ryegrass swards appeared to have little competitive advantage against weed invasion compared to the swards with less ryegrass, the established weed population (both broad-leaved weeds and volunteer grasses) was significantly lower in these plots. This presumably would lead to higher production from the sward and hence some payback for the additional ryegrass seed cost during establishment. Another advantage with the lower established weed population is that there would be less weed seed return to the seedbank. This would lead to fewer weed invasion problems in the future and thus the pasture would remain in a productive state for longer, giving the farmer more years of production before it required renewal.

A current trend in New Zealand is to use increasingly lower sowing rates when establishing pastures (Phil Rolston pers. comm.), and this has the potential to encourage weed invasion during establishment. Hampton *et al.* (1999) mentioned that sowing more grass seed per hectare will not necessarily increase the number of plants per hectare because the percentage of plants establishing decreases as sowing rate increases. Other studies have also proven that higher sowing rates have little effect on production. Frame & Boyd (1986) experimented with perennial ryegrass sowing rates of 10, 20 and 30 kg/ha, with 3 kg/ha white clover. They found that sowing rates had no effect on either total dry matter production or white clover yield. Nevertheless higher sowing rates have proved through competition to decrease the biomass of weeds establishing in a newly sown pasture (Cullen & Meeklah 1959, Seefeldt & Armstrong 2000). This present trial has led on from the results of Seefeldt & Armstrong (2000) and also indicates that lower ryegrass sowing rates leads to both higher weed and volunteer grass populations. Therefore, the current trend for lower sowing rates will in most cases lead to an increased weed population unless herbicides are applied.

So it appears that the goal of a high production pasture with a low weed population can be achieved in two ways: either through low sowing rates and herbicide applications to control weeds, or with high sowing rates which utilise competition to reduce weed numbers. The choices made by each farmer must then relate to the costs of each system (i.e. herbicide plus application versus seed costs) and also the farmer's individual priorities (i.e. goals to reduce herbicide use or labour costs etc.). For example, to apply the herbicide MCPB to an establishing pasture at the recommended rate of 3-4 L in 200 L of water per hectare (O'Conner 1996) with $9-15 / ha application costs (Burtt 1999) would cost a minimum of $39.38 and a maximum of $55.50 (these figures were calculated from a MCPB price of $202.50 / 20 L (Burtt 1999)). By comparison, uncoated perennial ryegrass seed, cultivar Bronsyn, costs $4.35 / kg (Burtt 1999) and therefore every extra 10 kg of seed per hectare will add a cost of $40.35. Therefore the amount of perennial ryegrass seed could be doubled from 10 kg / ha to 20 kg / ha for about the same price as one herbicide application. However, it must be noted that coated seed can more than double the price of the seed, although of course this is not an option for organic farmers. These figures indicate that to raise the sowing rate of perennial ryegrass significantly (i.e. 40 kg / ha +) would be an expensive option, and therefore only likely to be adopted by farmers whose management strategies prohibit the use of herbicides (i.e. organic farmers).

The high density ryegrass pasture could benefit organic growers especially as lower weed populations can be achieved without the use of herbicides. However, a major disadvantage is that a high density ryegrass sward will tend to out-compete slower growing beneficial grasses.

5.6. Conclusions

The experimental program reported on in this thesis endeavoured to determine whether there are any continued benefits in weed control with higher sowing rates of perennial ryegrass, once the pasture has established. Interestingly the only species that experienced a decline in emergence with increased sowing rates was Scotch thistle, and then this only occurred in the tray experiment. Significantly none of the sown weed species in the field had a decrease in emergence with increased sowing rate. Weed size was also only affected to a very limited extent by ryegrass sowing rates. The only real differences in weed size were between the trays that contained perennial ryegrass and those that did not. The lesser competitive effects exerted by the clover only plots and bare ground allowed weeds in these treatments to grow larger.

Therefore it would seem from these experiments that dense swards that contain perennial ryegrass appear to reduce weed invasion regardless of the sward composition. Hedge mustard is a good example of this whereby the presence of any vegetation resulted in negligible seedling emergence.

So, in conclusion it would appear from this study that the advantages from higher seeding rates of perennial ryegrass for weed control are obtained mostly in the first year, with the initial prevention of the weed population establishing when the pasture is resown. Any continued advantages from these higher seeding rates of perennial ryegrass are primarily related to the lower established weed population enabling higher production from the pasture, rather than an effect on establishing weeds.

References

Ahmed, M. & Wardle, D.A. (1993) Interference of rosette ragwort plants with forage plant emergence mortality and growth. *Proceedings of New Zealand Plant Protection Conference*, **46**, 295-296.

Ahmed, M. & Wardle, D.A. (1994) Allelopathic potential of vegetative and flowering ragwort (*Senecio jacobaea* L.) plants against associated pasture species. *Plant and Soil*, **164**, 61-68.

Anderson, W.P. (1996) *Weed science: principles and applications*. Third Edition. West Publishing Company, St Paul.

Anon. (1981) Pasture management for control of tansy ragwort. *Pacific Northwest Cooperative Extension Publication*, **210**.

Anon (1986) Deep weeds last longer. *New Zealand Agrichemical Manual Update*, **1(4)**.

Armstrong, M.L., Seefeldt, S.S. & Harrington, K.C. (2001) Effect of perennial ryegrass density on ragwort emergence. *New Zealand Plant Protection*, **54**, 111-115.

Baker-Kratz, A.L. & Macguire, J.D. (1984) Germination and dry matter accumulation in dimorphic achenes of tansy ragwort (*Senecio jacobaea* L.). *Journal of Ecology*, **72**, 265-322.

Beskow, W.B., Harrington, K.C., Betteridge, K. & Beskow, A.M.da.S. (1994) Field studies of ragwort establishment. *Proceedings of the New Zealand Plant Protection Conference*, **47**, 49-52.

Black, J.N. (1958) Competition between plants of different initial seed sizes in swards of subterranean clover (*Trifolium subterranean*) with particular reference to leaf area and the light microclimate. *Australian Journal of Agricultural Research*, **9**, 299-318.

Bouwmeester, H.J. & Karssen, C.M. (1989) Environmental factors influencing the expression of dormancy patterns in weed seeds. *Annals of Botany*, **63**, 113-120.

Bruere, A.N., Cooper, B.S. & Dillon, E.A. (1991) *Veterinary Clinical Toxicology*. Veterinary Continuing Education, Massey University, New Zealand.

Bullock, J.M., Clear Hill, B. & Silvertown, J. (1994) Demography of *Cirsium vulgare* in a grazing experiment. *Journal of Ecology*, **82**, 101-111.

Bullock, J.M. (1996) Plant competition and community dynamics. *The ecology and management of grazing systems*. (eds. A. Illius & J. Hodgson), pp. 69-100, Wallingford: CAB International.

Bullock, J.M., Clear Hill, B., Silvertown, J. & Sutton, M. (1995) Gap colonization as a source of grassland community change: Effects of gap size and grazing on the rate and mode of colonization by different species. *Oikos*, **72**, 273-282.

Bullock, J.M. & Marriott, C.A. (2000) Plant responses to grazing, and opportunities for manipulation. *Grazing management*. (eds. A.J. Rook & P.D. Penning), pp. 17-26. Occasional Symposium No. 34, British Grassland Society.

Burtt, E.S. (1999) *Financial budget manual*. Farm Management Group, Applied Management and Computing Division, Lincoln University.

Callaway, R.M. (1995) Positive interactions among plants. *The Botanical Review*. **61(4)**, 306-349.

Cameron, E. (1935) A study of the natural control of ragwort (*Senecio jacobaea* L.). *Journal of Ecology*, **23**, 265-322.

Caradus, J.R. & Chapman, D.F. (1991) Variability of stolon characteristics and response to shading in two cultivars of white clover (*Trifolium repens L.*). *New Zealand Journal of Agricultural Research*, **34**, 239-247.

Clements, F.E., Weaver, J.E. & Hanson, H. (1929) *Plant competition*. Carnegie Institute of Washington. Publication No. 398.

Clough, T.J. (1993) Seed technology: Purchase and storage of small seed. *Pasture Renovation Manual*. (eds. R.P Pottinger, P.M.S. Lane & J.R. Wilkens), pp. 34-37. New Zealand Pastoral Agricultural Research Institute Ltd.

Clough, T.J. & Hay, R.J.M. (1993) Pasture species and cultivars. *Pasture Renovation Manual*. (eds. R.P Pottinger, P.M.S. Lane & J.R. Wilkens), pp. 25-33. New Zealand Pastoral Agricultural Research Institute Ltd.

Cocks, P.S. (1974) The influence of density and nitrogen on the outcome of competition between two annual pasture grasses (*Hordum leporinum* Link and *Lolium rgidum* Gaud.). *Australian Journal of Agricultural Research*. **25**, 247-258.

Cullen, N.A. (1964) Species competition in establishing swards: suppression effects of ryegrass on establishment and production of associated grasses and clovers. *New Zealand Journal of Agricultural Research*, **7**, 678-693.

Cullen, N.A. (1966) Invermay trials show importance of competition between pasture species. *New Zealand Journal of Agriculture*, **112(2)**, 31-33.

Cullen, N.A. & Meeklah, F.A.H. (1959) Seeding rates and weedkillers in pasture weed control. *Proceedings of the New Zealand Weed Control Conference*, **12**, 54-58.

Davidson, J.L. & Donald, C.M. (1958) The growth of swards of subterranean clover with particular reference to leaf area. *Australian Journal of Agricultural Research*, **9**, 53-73.

Deschenes, J.M. (1973) Intraspecific competition in experimental populations of weeds. *Canadian Journal of Botany*. **52**, 1415-1421.

Doucet, C. & Cavers, P.B. (1996) A persistent seed bank of the bull thistle *Cirsium vulgare*. *Canadian Journal of Botany*, **74**, 1386-1391.

Earhart, D.R. & Fuqua, M.C. (1979) The effect of temperature and moisture levels on germination of the triploid watermelon, *Citrullus vulgaris*. *Hortscience*, **14(2)**, 123.

Edmonds, D.K. & Popay, A.I. (1983) Effect of pasture competition on the survival and flowering of nodding thistle. *Proceedings of the New Zealand Weed and Pest Control Conference*, **36**, 89-92.

Featherstone, C.I. (1957) The progress of chemical weed control in Hawkes Bay. *Proceedings of the New Zealand Weed Control Conference*, **10**, 7-12.

Fenner, M. (1985) *Seed Ecology*. Chapman and Hall, London, U.K.

Forcella, F. & Wood, H. (1986) Demography and control of *Cirsium vulgare* (Savi) Ten. in relation to grazing. *Weed Research*, **26**, 199-206.

Frame, J. & Boyd, A.G. (1986) Effect of cultivar and seed rate of perennial ryegrass and strategic fertilizer nitrogen on the productivity of grass/white clover swards. *Grass and Forage Science*, **41 (4)**, 359-366.

Gill, G.S. & Davidson, R.M. (2000) Weed Interference. *Australian Weed Management Systems*. (ed. B.M. Sindel). R.G. and F.J. Richardson Publishers, Victoria, Australia.

Goldberg, D.E. & Werner, P.A. (1983) The effects of size of opening in vegetation and litter cover on seedling establishment of goldenrods (Solidago spp.). *Oecologia*, **60**, 149-155.

Grime, J.P., Mason, G., Curtis, A.V., Rodman, J., Band, S.R., Mowforth, M.A.G., Neal, A.M. & Shaw, S. (1981) A comparative study of germination characteristics in a local flora. *Journal of Ecology*, **69**, 1017-1061.

Groves, R.H. & Kaye, P.E. (1989) Germination and phenology of seven introduced thistle species in Southern Australia. *Australian Journal of Botany*, **37**, 351-359.

Hampton, J.G., Kemp, P.D. & White, J.G.H. (1999) Pasture establishment. *New Zealand pasture and crop science*. (eds. J. White & J. Hodgson), pp. 101-115. Oxford University Press.

Harper, J.L. (1958) The ecology of ragwort (*Senecio jacobaea* L.) with special reference to control. *Herbage Abstracts*, **28**, 151-157.

Harper, J.L. (1961) Approaches to the study of plant competition. *Symposia of the Society for Experimental Biology*, **15**, 1-39.

Harper, J.L. (1977) *Population biology of plants*. Academic Press. London.

Harper, J.L. & Gajic, D. (1961) Experimental studies of the mortality and plasticity of a weed. *Weed Research*: **1**, 91-104.

Harper, J.L. & Wood, W.A. (1957) Biological flora of the British Isles. *Journal of Ecology*, **45**, 617-637.

Harrington, K.C. & Popay, A.I. (1987) Differences in susceptibility of nodding thistle populations to phenoxy herbicides. *Proceedings of the Australian Weeds Conference*, **8**, 126-129.

Hartley, M.J. (1983) Effect of Scotch thistles on sheep growth rates. *Proceedings of the New Zealand Plant Protection Conference*, **36**, 86-89.

Hewitt, E.J. (1966) Sand and water culture methods used in the study of plant nutrition. *Commonwealth Bureau of Horticulture and Plantation Crops Technical Communication No. 22.*

Hexter, G.W. (1950) Ragwort: control by pasture improvement. *Journal of the Department of Agriculture Victoria*, **48**, 217-218.

Hilhorst, H.W.M. (1990) Dose-response analysis of factors involved in germination and secondary dormancy of seeds of *Sisymbrium officinale*. I. Phytochrome. *Plant Physiology*, **94**, 1090-1095.

Hill, M.J. & Luck, R. (1991) Germination and seedling growth of legumes. *Australian Journal of Agricultural Research*, **42,** 175-189.

Hilhorst, H.W.M. (1990) Dose-response analysis of factors involved in germination and secondary dormancy of seeds of *Sisymbrium officinale*. II. Nitrate. *Plant Physiology*, **94**, 1096-1102.

Hodgson, G.L. & Blackman, G.E. (1956) An analysis of the influence of plant density on the growth of *Vicia faba*. I. The influence of density on the pattern of development. *Journal of Experimental Botany*. 7, 147-165.

Holland, P.T. & Rahman, A. (1999) *Review of trends in agricultural pesticide use in New Zealand.* MAF Policy Technical Paper 99/11. Ministry of Agriculture and Forestry, Wellington, 53 pp.

Holliday, R. (1960) Plant population and crop yield. *Nature*. **186**, 22-24.

Hulten, E. & Fries, M. (1986) *Atlas of North European Vascular Plants North of the Tropic of Cancer II*. Koeltz Scientific Books, Konigstein.

Inouye, R.S. (1980) Density-dependent germination response by seeds of desert annuals. *Oecologia*, **46**, 235-238.

Ivens, G.W. (1979) Nodding thistle. *New Zealand Journal of Agriculture*, **138**, 16-19.

Ivens, G.W. & Taylor, R. (1985) *The New Zealand garden weed book: A guide to identification and control*. Reed Methven Publishers.

James, T.K., Rahman, A., Wardle, D.A. & Bonner, K.I. (1998) Survival of nodding thistle (*Carduus nutans*) seed buried at different depths in four soils. *New Zealand Plant Protection Conference*, **51**, 33-37.

Karssen, C.M. & De Vries, B. (1983) Regulation of dormancy and germination by nitrogenous compounds in the seeds of *Sisymbrium officinale* L. (hedge mustard). *Aspects of Applied Biology*, **4**, 47-54.

Kays, S. & Harper, J.L. (1974) The regulation of plant and tiller density in a grass sward. *Journal of Ecology*, **62**, 97-105.

Kelly, D. & McCallum, K. (1990) Demograhy, seed biology and biological control of *Carduus nutans* in New Zealand. *Biology and control of invasive plants*, pp 72-79.

Klinkhamer, P.G.L. & De Jong, T.J. (1993) *Cirsium vulgare* (Savi) Ten. *Journal of Ecology*, **81**, 177-191.

Klinkhamer, P.G.L., de Jong, T.J. & van der Meijden, E. (1988) Production, dispersal and predation of seeds in the biennial *Cirsium vulgare*. *Journal of Ecology*, **76**, 403-414.

L'Huiller, P.J. (1987) Tiller appearance and death of *Lolium perenne* in mixed swards grazed by dairy cows at two stocking rates. *New Zealand Journal of Agricultural Research*, **30**, 15-22.

Linhart, Y.B. (1976) Density-dependent seed germination strategies in colonizing versus non-colonizing plant species. *Journal of Ecology*, **64**, 375-380.

Lonsdale, W.M. & Watkinson, A.R. (1982) Light and self-thinning. *New Phytologist*, **90**, 431-445.

McGowan, G.S. & Wallace, J.W. (1972) Flavonoids and phenolic acids from *Cirsium lanceolatum*. *Phytochemistry*, **11**, 1503-1504.

McKenzie, B.A., Valentine, I., Matthew, C. & Harrington, K. (1999) Plant interactions in pastures and crops. *New Zealand Pasture and Crop Science* (eds. J. White & J. Hodgson), pp 45-58. Oxford University Press.

Medd, R.W. & Lovett, J.V. (1978) Biological studies of *Carduus nutans* (L.) ssp. *nutans* 1. Germination and light requirement of seedlings. *Weed Research*, **18**, 363-367.

Mitch, L.M. (1998) Bull thistle, *Cirsium vulgare*. *Weed Technology*. **12**, 761-763.

Morrison, S.L. & Molofsky, J. (1998) Effects of genotypes, soil moisture, and competition on the growth of an invasive grass, *Phalaris arundinacea* (reed canary grass). *Canadian Journal of Botany*. **76**, 1939-1946.

Nicholson, K.S., Rahman, A. & Wardle, D.A. (1990) Interactions between establishing nodding thistle and pasture seedlings. *Proceedings of the New Zealand Weed and Pest Control Conference*, **43**, 225-228.

O'Conner, B. (1996) *Novachem manual. A New Zealand guide to agrichemicals for plant protection*. Novachem Services Limited.

Palmblad, I.G. (1968) Competition in experimental populations of weeds with emphasis on the regulation of population size. *Ecology*. **49(1)**, 26-34.

Panetta, F.D. & Wardle, D.A. (1992) Gap size and regeneration in a New Zealand dairy pasture. *Australian Journal of Ecology*, **17**, 169-175.

Peters, N.C.B., Atkins, H.A. & Brain, P. (2000) Evidence of differences in seed dormancy among populations of *Bromus sterilis*. *Weed Research*, **40**, 467-478.

Phung, H.T. & Popay, A.I. (1981) Effect of pasture cover on the germination of certain weed seeds. *Proceedings of the New Zealand Weed and Pest Conference*, **34**, 111-113.

Poole, A. L. & Cairns, D. (1940) Botanical aspects of ragwort (*Senecio jacobaea*) control. *Department of Scientific and Industrial Research*, Bulletin. No. **82**, Wellington.

Popay, A.I. & Medd R.W. (1990) The biology of Australian weeds. 21. *Carduus nutans* L. ssp. *nutans*. *Plant Protection Quarterly*, **5**, 3-13.

Popay, A.I. & Thompson, A. (1979) Some aspects of the biology of *Carduus nutans* in New Zealand pastures. *Proceedings of the Asian-Pacific Weed Science Society Conference*, 7, 343-346.

Popay, A.I., Thompson, A. & Bell, D.D. (1987) Germination and emergence of nodding thistle (*Carduus nutans* L.). *Proceedings of the Australian Weeds Conference*, **8**, 175-178.

Puckridge, D.W. & Donald, C.M. (1967) Competition among wheat plants sown at a wide range of densities. *Australian Journal of Agricultural Research*, **18**, 193-211.

Putnam, A.R. (1985) Weed Allelopathy. *Weed Physiology. Vol. I: Reproduction and Ecophysiology*. (ed. S.O. Duke), pp 131-148. CRC Press.

Rahman, A., James, T.K. & Bourdot, G.W. (1993) Weed Control. *Pasture Renovation Manual*. (eds. R.P Pottinger, P.M.S. Lane & J.R. Wilkens), pp. 78-86. New Zealand Pastoral Agricultural Research Institute Ltd.

Rejmanek, M., Robinson G.R. & Rejmankova, E. (1989) Weed-crop competition: experimental designs and models for data analysis. *Weed Science*. **37**, 276-284.

Risser, P.G. (1969) Competitive relationships among herbaceous grassland plants. *Botanical Review*, **35**, 251-284.

Roy, B., Popay, I., Champion, P., James, T. & Rahman, A. (1998) *An illustrated guide to common weeds of New Zealand*. New Zealand Plant Protection Society.

Sangakkara, R., Roberts, E. & Watkin, B.R. (1982) Grass species used and pasture establishment practices in central New Zealand. *New Zealand Journal of Experimental Agriculture*, **10**, 359-364.

Seefeldt, S.S. & Armstrong, M.L. (2000) Impact of perennial ryegrass seeding densities on weed emergence, growth and development. *New Zealand Plant Protection*, **53**, 38-43.

Sindel, B.M. (1991) A review of the ecology and control of thistles in Australia. *Weed Research*, **31**, 189-201.

Smetham, M.L. (1990) Pasture assessment for livestock managers. *Pastures – their ecology and management*. (ed. R.H.M. Langer), pp 197-240 Oxford University Press.

Taylor, R.L. (1980) *Weeds of crops and gardens in New Zealand*. R.L.Taylor, Nelson.

Thompson, A. (1985) Population studies on ragwort (*Senecio jacobaea*). *Proceedings of the New Zealand Weed and Pest Control Conference*, **38**, 122-126.

Thompson, K., Grime, J.P. & Mason, G. (1977) Seed germination in response to diurnal fluctuations of temperature. *Nature*, **267**, 147-149.

Thompson, A. Saunders, A.E. & Martin, P. (1987) The effect of nodding thistle (*Carduus nutans*) on pasture production. *Proceedings of the New Zealand Weed and Pest Control Conference*, **40**, 222-225.

Turkington, R, & Harper, J.L. (1979) The growth, distribution and neighbour relationships of *Trifolium repens* in a permanent pasture. I. Ordination, pattern and contact. *Journal of Ecology*, **67**, 201-218.

Turkington, R. & Jolliffe, P.A. (1996) Interference in *Trifolium repens – Lolium perenne* mixtures: short- and long-term relationships. *Journal of Ecology*. **84**, 563-571.

van der Meijden, E. & van der Waals-Kooi, R.E. (1979) The population ecology of *Senecio jacobaea* in a sand dune system. I. Reproductive strategy and the biennial habit. *Journal of Ecology*, **67**, 131-153.

Wardle, D. A. (1987) The ecology of ragwort – a review. *New Zealand Journal of Ecology*, **10**, 67-76.

Wardle, D.A., Nicholson, K.S. & Ahmed, M. (1991) Residual allelopathic effects of pasture grasses and legumes on nodding thistle seedling emergence and growth. *Proceedings of the New Zealand Weed and Pest Control Conference*, **44**, 284-287.

Wardle, D.A., Nicholson, K.S. & Rahman, A. (1992) Influence of pasture grass and legume swards on seedlings emergence and growth of *Carduus nutans* L. and *Cirsium vulgare* L. *Weed Research*, **32**, 119-128.

Wardle, D.A., Nicholson, K.S., Ahmed, M. & Rahman, A. (1995) Influence of pasture forage species on seedling emergence, growth and development of *Carduus nutans*. *Journal of Applied Ecology*, **32**, 225-233.

White, J.G.H. (1977) Pasture establishment. *Pastures and pasture plants* (ed. R.H.M. Langer), pp.129-155. A.H. & A.W.R. Reed, Wellington.

White, J. & Harper, J.L. (1970) Correlated changes in plant size and number in plant populations. *Journal of Ecology*, **58**, 467-485.

Yoda, K., Kira, T., Ogawa, H. & Hozumi, H. (1963) Self-thinning in overcrowded pure stands under cultivated and natural conditions. *Journal of Biology, Osaka City University*, **14**, 107-129.

Young, K.A. (1985) Seed dormancy. *Official Seed Testing Station Annual Report*. pp. 41-48. MAF New Zealand.

Zaleski, A. (1965) White clover investigations II. Effect of companion grasses and methods of sowing on seed production. *Journal of Agricultural Science*, **64**, 77-82.