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CONTRIBUTION OF CROP MORPHOLOGICAL CHARACTERISTICS AND DENSITY OF SELECTED CROPS TO WEED SPECIES COMPOSITION AND SUPPRESSION

A thesis

submitted in partial fulfilment

of the requirements for the Degree of

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by

Wendy Ann P. Isaac

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Abstract of a thesis submitted in partial fulfilment of the requirements for the degree of M.Appl.Sc.

Contribution of Crop Morphological Characteristics and Density of Selected Crops to Weed Species Composition and Suppression

by

Wendy Ann P. Isaac

A field study was conducted at Lincoln University during the 1999-2000 growing season to investigate the effect of crop species and sowing density on weed dynamics, productivity and species composition. Crops with a spreading (narrow-leafed lupin, *Lupinus angustifolius* and dwarf French bean, *Phaseolus vulgaris*), rosette (turnip, *Brassica campestris* and forage rape, *Brassica napus*) and upright (maize, *Zea mays*, and ryecorn, *Secale cereale*) growth habits were sown at 0.0, 0.5, 1.0, 2.0 and 4.0 times their optimum population. No other weed control measures were applied.

The six crops were sown on 8 September 1999 (early spring): narrow–leafed lupin, ryecorn and forage rape on and 4 November 1999 (early summer): dwarf French bean, maize and turnip. The weed seed bank prior to sowing was predominated by *Coronopus didymus*.

There were significant differences in the suppressive ability of the different crop species and different crop populations ($p < 0.001$). Weed dry matter (DM) was lowest in turnip (0.58 g/m^2) and highest in dwarf French bean (123.50 g/m^2) at final harvest.

By final harvest crop density had a marked effect on weed DM production. There was decreased weed DM at higher plant populations in all crop species, except turnip, at all plant populations. However, there were differences between 0.5 and 4.0 x optimum populations in bean (397 and 12 g/m^2), rape (189 and 26 g/m^2), lupin (125 and 7 g/m^2), maize (106 and 0 g/m^2) and ryecorn (51 and 18 g/m^2).

Weed suppression as affected by the different crop treatments was directly related to leaf area index (LAI), radiation interception and radiation use efficiency

(RUE). The highest LAI's were recorded in turnip (4.1) at 60 DAS, while other crops such as bean and maize attained LAI's of only 0.66 and 1.1 respectively by the same time. Leaf area index increased with increased plant population in all crops. Leaf area index in turnip at 60 DAS ranged from 3.5 at 0.5 x optimum population to 5.1 at 4.0 x optimum population. In maize LAI ranged from 0.4 to 2.0 at the same plant populations at the same time.

Canopy closure occurred at 50 DAS in turnip at 4.0 x optimum population, at 60 DAS for lupin, ryecorn and rape and at 83 DAS for maize and bean. Canopy closure was never attained at 0.5 x optimum population in lupin, rape, ryecorn, bean and maize.

Turnip intercepted the most solar radiation (SR) at 1068 MJ/m^2, which was 354 MJ/m^2 more than bean, which intercepted the least photosynthetic active radiation (PAR). Total intercepted PAR also increased with increased plant population. There was a strong linear relationship between cumulative intercepted PAR and cumulative DM yield in all crops. Maize produced more DM per MJ of intercepted PAR than all the other crops at 3.4 g DM MJ PAR^{-1} whereas lupin, ryecorn, rape, bean and turnip produced 1.7, 1.2, 0.98 and 0.37 g DM PAR^{-1} respectively.

Crops with large leaf size and rapid growth were effective in reducing the weed seed bank, weed species and numbers in the following growing season. The most effective reduction occurred with turnip followed by maize (55 and 66 x 10^3 seed/m^2 respectively) compared with lupin and rape which contained the highest (158 and 130 x 10^3 seeds/m^2 respectively). Weed seed production was markedly affected by plant population ($p < 0.05$). Higher plant populations (2.0 and 4.0 x optimum population) of lupin, rape, ryecorn and maize effectively suppressed weed seed production. Lower plant populations (0.5 and 1.0 x optimum population) contained higher weed seed numbers/m^2 in lupin, rape, ryecorn, bean and maize plots. *Coronopus didymus* was the most abundant species in the weed seed bank in the 2000-growing season.

Weed seedling emergence in the 2000-growing season also reflected previous crop treatments. Bean contained the highest weed seedling density (1,163 weed seedlings/m^2) and turnip the least (109 weed seedling/m^2). As plant population increased from 0.0 to 4.0 x optimum population weed density decreased. The decrease was most pronounced in lupin (1,128 to 466 weed seedlings/m^2), rape (1,082 to 319

weed seedlings/m^2) and ryecorn (1,308 to 362 weed seedlings/m^2). *Chenopodium album* was the most abundant weed species to emerge during the 2000. growing season.

A mechanistic model of crop and weed growth was tested for its ability to simulate DM accumulation of weed and crop in lupin. rape and ryecorn and used SR and LAI data. The model accurately predicted crop and weed DM for lupin. rape and ryecorn grown at the 4 crop densities. The model could be of practical value in predicting the potential weed DM yield under different crop species at different plant densities.

The results suggested that inclusion of large leaf size and rapid growth in selection of crop as competitors to suppress weeds by using crops such as turnip; maize and ryecorn should be feasible in a weed management program.

Keywords: narrow-leafed lupin. (*Lupinus angustifolius*). dwarf French bean. (*Phaseolus vulgaris*). turnip (*Brassica campestris*). forage rape (*Brassica napus*) maize. (*Zea mays*). ryecorn (*Secale cereale*). *Trifolium repens*. *Coronopus didymus*. leaf area index (LAI). radiation interception. radiation use efficiency (RUE). photosynthetic active radiation (PAR). *Chenopodium album*. mechanistic model. solar radiation (SR)

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List of Abbreviations

CV	-	Coefficient of variation
cv.	-	Cultivar
DAE	-	Days after emergence
DAS	-	Days after sowing
df	-	degree of freedom
DM	-	Dry matter
FC	-	Field capacity
g	-	gram
GC	-	Ground cover
GR	-	Growth rate
ha	-	hectare
HI	-	Harvest index
kg	-	Kilogram
LAI	-	Leaf area index
LSD	-	Least significant difference
LTM	-	Long term mean
m^2	-	square meter
MJ	-	Megajoule
ns	-	not significant
^{o}C	-	degree Celsius
PAR	-	Photosynthetically active radiation
PCA	-	Principle Component Analysis
PPD	-	Plant Population Density
%	-	Percentage
RSMD	-	Root square mean difference
RUE	-	Radiation use efficiency
SED	-	Standard error of mean difference
SEM	-	Standard error of mean
sp.	-	Species
SR	-	Solar radiation
t	-	Tonne
Temp.	-	Temperature

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Chapter 1

General Introduction

1.1 Background

Food losses due to weeds have been estimated at 20 % in most developing countries and about 10 % in developed countries. Losses due to weeds, if not curbed, are usually significantly higher than those caused by diseases or insect pests (Kropff and Walter, 2000). In a given year, these losses ultimately arise from the population dynamics, biology and ecology of both crop and weeds, particularly during their early development (Alteri, 1988). Weeds interfere adversely with cropping systems primarily by:

(1) reducing the growth and yield of crops due to competition for the limited resources of light, water and nutrients;

(2) reducing the financial value of the product to be harvested, mainly by contaminating the crop produce, reducing its size and quality.

Thus, weeds must be controlled to avert financial losses as they reduce profits by lowering output, increasing expenses and reduce quality.

The management of weeds was a key issue in agricultural production systems even before the advent of the herbicide revolution. Since their invention in the 1940's, herbicides and other high energy based inputs have resulted in the intensification of agriculture, particularly in developed countries. Since the introduction of herbicides in the mid- 1950's, scientific research on weeds has mainly been herbicide driven (Van der Zweep and Hance, 2000). Extensive use of herbicides over the years, aimed at the total eradication of weeds, has significantly alleviated weed problems in the short term (Alteri, 1988). However, heavy inputs and mis-use (in most cases stimulated by efforts in pursuit of short-term gains by farmers) have been identified as major contributors to the destruction of fragile ecosystems in many countries. In addition to these environmental safety concerns, this heavy use and mis-use of herbicides has contributed to rapid weed flora shifts and the development of herbicide resistance in many weed species (Bridgemohan, 1993).

These problems have in recent years prompted increased research into a more integrated approach to weed management and the use of alternative methods for weed control to reduce these negative effects. Instead of total eradication of weeds from the field, emphasis must now be on the management of weed populations. An understanding of the biology, ecology and population dynamics of weeds, and how they interact with the crop, is important for the development of an economically sound, integrated approach to weed management (Liebmann and Davis, 2000; Rahman *et al.*, 2000).

Successful weed management as identified by Regehr and Thomas (1994), is most readily attained where the knowledge of weed and crop biology, cultural practices that favour vigorous crop growth, mechanical weed control, and herbicide technology are brought together in carefully planned systems. Such integrated weed management, he further explained is characterised by processes and practices that complement and reinforce each other, to exploit weaknesses in weed species. Liebmann and Davis (2000) emphasised the need to reduce the use of herbicides. They also stressed that low-external–input (LEI) farming systems should be employed to ameliorate economic and environmental effects, shifts in weed populations and communities, and the health risks of exposure to agrochemicals associated with conventional farming systems.

1.2 Justification

In New Zealand, as in many other developed countries, there is interest in reducing pesticide use and an increased interest in organic farming (Seefeldt and Armstrong, 2000). Weeds however, continue to be a major concern in conventional farming systems as their control is still essentially by herbicides. These chemicals account for 68 % of the total pesticide active ingredient applied in New Zealand (Holland and Rahman, 1999). Despite the control methods presently used, crop losses caused by weeds are still of the same magnitude as those caused by pests and diseases Oerke *et al.*, (1994). At a Symposium on 'Organic Farming, 2000' held in Christchurch, New Zealand scientists drew attention to the fact that weeds and their control is still underrated. They stressed the urgency of the need to address the problems associated with weeds by increased research into environmentally sound control techniques.

There is an extensive literature on the effects of herbicides on weeds as well as on the competitive nature of weed on crops. However, there is a dearth of information on the phytotoxic effects of herbicides on crop yield and even less on the effects of crops on weeds

(Lotz *et al.*, 1996; Kropff and Walker, 2000). In this context, the selection of crops as part of an integrated approach to weed management is particularly important. To select crops, which may be effective at controlling weeds, it is important to determine the morphological and physiological attributes, associated with their competitive ability. This could assist in breeding more competitive crops, which could be used in effective crop rotations (Lermerle *et al.*, 1996 a). Additionally, other factors could be used synergistically with crop competitiveness to further enhance the crop's competitive ability over the weed such as varying the plant density and the spatial arrangement (Malik *et al.*, 1993; Paolini *et al.*, 1999).

1.3 Research objectives

In response to the above concerns the following objectives were formulated:

The overall objective of the research was to identify the factors that regulate the ecology and dynamics of weed populations in response to crop morphology and density. To examine weed management strategies based on weed suppression by a range of morphologically different crops over a cropping season.

The study was planned to:

1. Assess the impact of crop type and population density on weed-crop interactions and on the growth and development of the crop.
2. Study the effect of morphologically different crops on the weed species composition and production and to identify those morphological crop characteristics that are desirable for suppression of weed growth.
3. Compare the performance of a simple simulation model with independent field data on the critical period of weed competition in early sown crops and to use the model to evaluate the influence of crop and weed leaf area using comparisons with the crop biomass accumulation.
4. Determine the temporal changes of the weed species composition as affected by crop treatments in the preceding year.

Chapter 2

Literature Review

2.1 Introduction

The intensification of agriculture during the last 5 decades would not have been possible without widespread use of agrochemicals offering an effective and reliable method of weed control. Increasing environmental concerns, the need for reduced costs, and increased herbicide resistance in weeds has prompted research in recent years on alternative, sustainable management systems that reduce the need for agrochemicals.

A recent report by MAF (2000) found that there has been a decline in the use of hormone herbicides and an increase in phosphonyl herbicides (mainly glyphosate), triazine and sulfonylurea herbicides in New Zealand, indicating the changes in land use (more forestry), and cost-effectiveness (more glyphosate and sulfonylurea). Herbicides, were the most commonly used pesticide reported, (2,143 t) accounting for 68 % of the total active pesticide ingredient applied, followed by fungicides at 24 % and insecticides at 8.2 % (Holland and Rahman, 1999). The phosphonyl herbicides (mainly glyphosate) were the largest class (831 t), followed by phenoxy hormone herbicides (743 t), dithiocarbamate fungicides (366 t) and triazine herbicides (245 t). The trends in pesticide use in New Zealand from 1984 to 1998 in t of active ingredient are shown in Figure 2.1 and the changes in the uses of several important herbicide classes between 1986 and 1998 are shown in Figure 2.2.

Overall the trends show that the broad-spectrum phosphonyls, principally glyphosate now dominate in New Zealand. This could be attributed to their wide range of uses, high cost-effectiveness, low persistence in the soil and lack of ill effects on mammalian and human health and the environment. Phenoxy hormone herbicides have experienced a small drop in use. However, the use of 2,4-D and MCPA for broadleaf weed control is still common and triazine herbicide use has increased by 90 %. This dependency has been attributed to increased use in cropping and in forestry.

Herbicides, particularly phenoxies and sulphonyl ureas (eg. Glean), are used extensively for broadleaf weed control in cereal and herbage seed production in Canterbury. In field peas (*Pisum sativum*), which is the major grain legume in New Zealand herbicide, treatments are mainly with triazine and phenoxy herbicides.

Herbicides are the main pesticides used in maize (*Zea mays*): mainly amides (alachlor, acetochlor) and triazines (atrazine etc.).

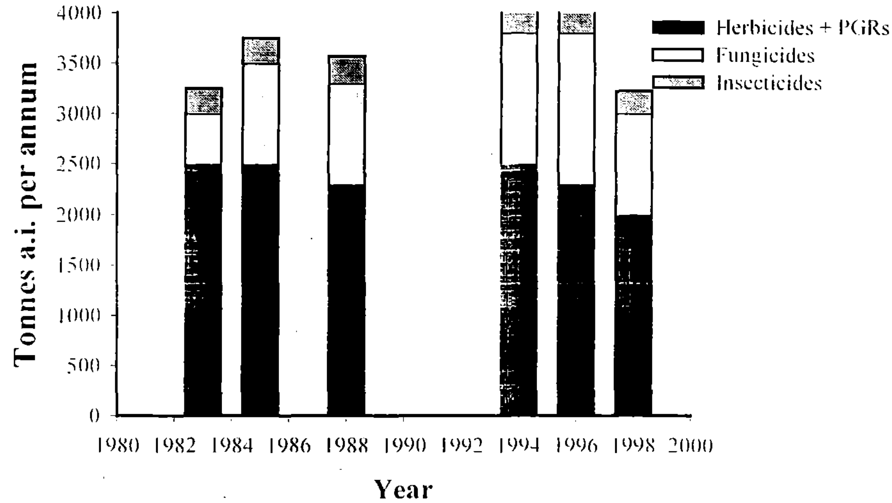

Figure 2.1: Pesticide use in New Zealand 1984-1998 (tonnes of active ingredient (a.i.)).

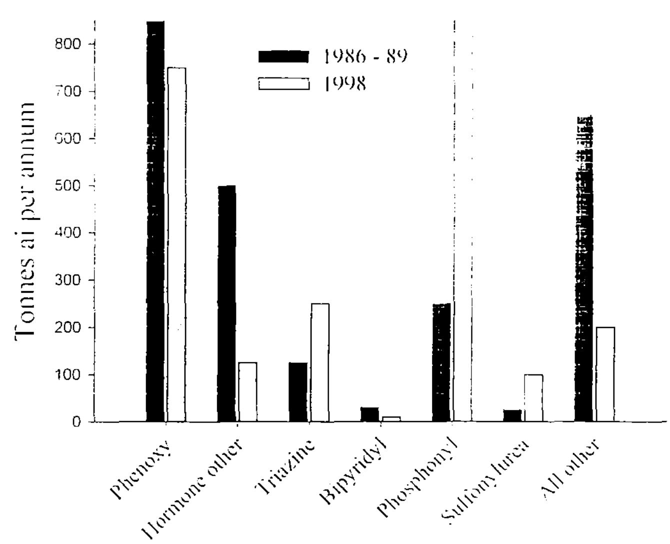

Figure 2.2: Herbicide use by class – comparison between 1986-89 and 1998.

Vegetable crops such as asparagus (*Asparagus officinalis*), green pea (*Pisum sativum*) and sweet corn (*Zea mays*) require heavy inputs of residual triazines, bromacil and phenoxies to control weeds. Holland and Rahman (1999) noted that the amount of triazines used is high and there is a threat of leaching of their residues into ground water in areas with light, free-draining soils. Table 2.1 shows the herbicide use in the various farming sectors for 1998 and Appendix 1 shows herbicide use in 3 crops grown in Canterbury in 1998, 1999.

In pastoral farming there is evidence that the extensive usage of phenoxy hormone products for broadleaf control in pastures has increased the spectrum of weed species exhibiting resistance to these herbicides such as nodding thistle (*Carduus nutans*) (Harrington, 1988, 1989) and giant buttercup (*Ranunculus acris*) (Bourdôt *et al.*, 1994, 1996) in some areas.

In concluding statements in the MAF report, Holland and Rahman (1999) noted that herbicide is the most cost-effective technology for weed control and that often there is no realistic alternative. However, they highlighted that the "MAF should develop policies on pesticide use which are integrated for sustainable agriculture and which address the key issues of identifying unacceptable risks from current use practices, development of alternative plant protection strategies, encouraging safer pesticide handling and more targeted application, and increasing end user confidence to adopt alternative practices" (Holland and Rahman, 1999).

Efforts must address the reduction in the extensive use of herbicides using alternative or a more integrated approach to weed management in New Zealand. This effort to control weeds without extensive herbicide inputs would consist of three components according to Lotz *et al.*, (1995). The first component would be to control weeds only at the economic threshold level, in other words where weeds are controlled only if the cost of control measures is less than the increased return on yield. The second component would be to reduce the herbicide input through proper and selected application methods. By putting less pesticide into the environment, the risk of pollution and weed resistance is reduced. Bridgemohan (1993) noted that this can be achieved by banding application of herbicides, using low volumes to improve glyphosate performance, proper timing of post emergence herbicides, use of herbicide combinations at low rates, use of newer, more active and more rapidly degraded herbicides. In addition, chemical control can be replaced by alternative practices such as mechanical or biological weed control.

A third component suggested by Lotz *et al.*, (1995) involves the possibility of decreasing the need for weed control by crop manipulation. This could be achieved by increasing the relative competitiveness of the crops in a rotation (e.g. by selecting more competitive cultivars or crops), or by optimising the competitive ability of the crop through general cropping practices (e.g. with respect to crop sowing date, crop density, and nitrogen supply). Recent research by Christensen *et al.*, (1994) and Grundy *et al.*, (1997) showed that both choice of crop and cultivar and crop density can be effective in suppressing weeds. Thus, herbicide inputs can be minimised, as there are a number of morphological traits that confer specific crop cultivars with greater competitive ability with weeds. A thorough quantitative insight into the crop-weed interaction is needed to be able to predict yield losses, to assess risks of less effective control methods and to explore ideas to improve the relative competitive ability of crops.

At the Second International Weed Control Congress, in Copenhagen, Kropff *et al.*, (1996) stressed that for the development of improved weed management systems, with reduced dependency on herbicides, an insight into the population dynamics of weeds and the interactions between the crop and the weeds is necessary. Such insights they suggested may help to identify opportunities for new control techniques that break weed life cycle at some point in time, to develop strategies for weed management.

2.2 The distribution of problem weed species in Canterbury

Holm *et al.*, (1977) reported that, of the world's worst weeds, 72 % are monocots, 44 % are perennials, 61 % reproduce vegetatively, and 33 % reproduce by rhizomes. The most troublesome weeds in New Zealand were introduced from Australia, Asia, Europe, North and South America and Africa and are now of economic significance. Forty four percent of these weeds are wild flowering plants (Parham and Healy, 1985). Many of these weeds include species that invade cultivated, arable and waste lands, gardens, road sides, pastures, farm yards, sheep camps and low tussock grasslands. Of the weeds that have invaded pastures and arable lands in the South Island, *Chenopodium album, Cirsium arvense, Rumex crispus, Capsella bursa-pastoris, Polygonum aviculare, Taraxacum officinale, Solanum nigrum* and others appear to have become very successful weed species.

Table 2.1: New Zealand national herbicide use in various sectors for 1998.

Sector	National acreage (10^3 ha)	Average Use (kg a.i./ha/annum)
Arable farming		
Cereals (wheat & barley)	120	156.000
Grass Seed	26	80.600
Legume Seed	14	9.800
Field peas	20	34.000
Maize (grain & silage)	28	126.000
Horticulture		
Apples	15	48.000
Kiwifruit	10	17.000
Grapes	10	29.000
Vegetables		
Potatoes	14	22.400
Onions	5	34.000
Brassicas	4	1.200
Green peas	10	16.000
Field tomatoes	2	7.200
Pastoral		
Sheep & beef	11.890	475.600
Dairy	1.270	355.600
Forestry (year 0/1 and 2)	205	820.000

Adapted from: Review of Trends in Agricultural Pesticides Use in New Zealand. MAF Policy Technical Paper 99/11. Ministry of Agriculture and Forestry (Holland and Rahman 1999).

Research on the weed flora associated with cereal crops (wheat (*Triticum aestivum*, cv. Otane and barley *Hordeum vulgare*, cv. Corniche) in Canterbury, New Zealand by Bourdôt *et al.*, (1998) indicated that a total of 23 families were present, with the Asteraceae, Brassicaceae, Caryophyllaceae, Fabaceae, and Polygonaceae being the most predominant. Annuals were more common (29 taxa) than perennials (12 taxa), whereas biennials (4 taxa) were the least frequent. Weed population densities varied greatly among species, but there was less variation between years and crop type. In the weed survey conducted by Bourdôt *et al.*, (1998) more than 57 weed species in more than 49 genera were recorded. Of the most frequently occurring weeds recorded, *Trifolium* sp. (mainly *Trifolium repens*), *Capsella bursa-pastoris*, *Viola arvensis*, *Stellaria media*, *Polygonum aviculare*, *Chenopodium album* and *Anagallis arvensis* present in most of the crops sampled.

Chenopodium album (fathen) is one of the most widely distributed weed species in the world. In many countries, for instance, it is the principal weed of barley and chickpea (*Cicer arietinum*); in the United States, it is considered the fourth most important weed in wheat (Harper and Gajic, 1961; Koch and Hess, 1980); and it ranks among the top three important weeds in cereals in New Zealand. Holms *et al.*, (1977) noted that this erect annual weed exhibits great plasticity in its response to the environment when it is in the proximity of neighbouring plants. The plant can grow to a height of 3 m if it grows in crops such as corn (*Zea mays*) and sorghum (*Sorghum bicolor*) where there is abundant availability of nutrients, and water. However, in waste places the weed tends to be small and insignificant. In studies by Plew (1994), *Chenopodium album* dominated the weed spectrum primarily because of its ability to mature rapidly and seed prolifically (Ivans and Taylor, 1985). *Chenopodium album* also competed strongly with corn for nitrogen, potassium, calcium and magnesium (Vengris, 1955).

Cirsium arvense (Californian thistle) is also a major weed. Just one plant can colonise an area several square meters in diameter during the first one or two seasons of its growth. Small fragments of roots can also give rise to new plants. Henskens *et al.*, (1996) suggested that its persistence can been attributed to the possession of substantial below ground reserves and adventitious root buds. This erect perennial herb together with its annual relative species *C. vulgare* are of particular importance in the South Island of New Zealand where they cause serious yield losses in many crops such as barley, corn, and other cereals (Bourdôt and Field, 1988). A considerable amount of research has recently been conducted on the control of this weed by Bourdôt *et al.*, (1996, 2000).

Achillea millefolium (yarrow) is also considered a successful and aggressive weed that is common in arable land in New Zealand. It causes significant crop losses in a variety of crops (Bourdôt and Field, 1988) by choking them out due to its dense growth habit. According to Henskens *et al.*, (1996), the weed was originally sown in New Zealand as a pasture species in the steeper drier areas of the South Island. Bourdôt and Field (1988) state that the weed lost favour in pastures as it displaced more productive species. It was soon regarded as a weed of arable land. The success of this weed is attributable to its persistent and vigorous rhizomes (Hartley *et al.*, 1984).

It is assumed that the differences among plant species in their morphology and patterns of growth influence their ability to acquire resources and consequently their competitive ability. Research by Gross *et al.*, (1992) on comparison of root morphology, growth rate and topology of seedlings of 12 herbaceous weeds, including fathen and yarrow and others that occurred in early to mid-successional fields, revealed significant differences among species that were largely related to their life history. They found that annuals grew faster and produced larger and more branched roots than biennials and perennials. Among the annuals, there was a positive correlation between seed mass and root growth. Grasses allocated proportionally more biomass to roots than the dicotyledons, but did not differ in their root length or branching.

2.3 The dynamics of weed populations

The development of integrated weed management systems that are economically sound requires a thorough understanding of the dynamics of weed populations (Walker and Buchanan, 1982; Fernandez-Quintanilla, 1988; Zimdhal 1995). Rahman *et al.*, (2000) indicated that bio-economic weed management models, which use seed bank estimates to predict weed population dynamics and competitiveness provide a good starting point for an integrated weed management program. The analysis of these populations is very complex as each population is composed of individuals in various functional stages, interacting with each other, with populations of other species and with the environment (Fernandez-Quintanilla, 1988). The major approaches that are available for the analysis of the population dynamics of weeds are (1) long-term studies where a single component of the population of a certain weed is monitored over several years, (2) demographic studies and (3) mechanistic models.

Weed population dynamics refers mainly to the changes that occur in the abundance, distribution and genetic structure of populations of weed species over time. Dramatic changes occur from year to year in the abundance of one species while other species may remain invariable (Cousens and Mortimer, 1995). In a few years some species may escalate and become problematic over a whole region while other species may decline and become extinct. In many cases, according to Mortimer (1990), weed control practices which were aimed at forestalling damage by weeds, have acted as a powerful force in the interspecific selection of weed flora. Figure 2.3 illustrates a schematic representation of a population dynamics model for weeds.

Cousens and Mortimer (1995) noted that plant species may be *pre-adapted* to be weeds in the sense that a species possesses a suite of life history characteristics that enables rapid population growth in the particular habitat conditions created and maintained by human activity. These *pre-adapted* weeds are defined as those species which are either resident in the plant's natural community within dispersal distance of the crop (or other habitat) and may come to predominate within the crop as a consequence of a change in crop husbandry practices.

The demography of a weed can be divided into two fractions, according to Fernandez-Quintanilla (1988): one active (the growing plants) and one passive (the dormant seeds and underground buds). Demographic studies offer some insights into the processes and factors that regulate the sizes of populations. In mechanistic studies on the other hand, the life cycles of the population must be broken down into a large number of components representing the various stages of plant growth and development. In such studies, the major physiological and ecological processes involved in the cycle should be considered, including environmental conditions.

Studies on the effect of crops on the population dynamics of the weed nutsedge (*Cyperus esculentus*) were done by Lotz *et al.*, (1991). After six years cropping with maize, the effects of one year cropping of maize, fibre hemp (*Cannabis sativa*), winter barley (*Hordeum vulgare*), winter rye (*Secale cereale*), and of no crop were assessed on the tuber production per weed plant. In the hemp, there was hardly any tuber production. However in other crops the reproduction of the weed was 3 to 50 tubers per plant. The after effects of the different crops on the density of the primary shoots of nutsedge in a following maize crop were studied. The weed density was substantially reduced after growing hemp, whereas it was increased after growing the other crops. From additional shading experiments, Lotz *et al.*, (1991) concluded that competition for light was the main factor explaining the observed crop effects on the reproduction of the weed. These results suggested that selecting highly competitive crops, like hemp, might be an important mechanism in achieving reductions in herbicide input in crop rotations.

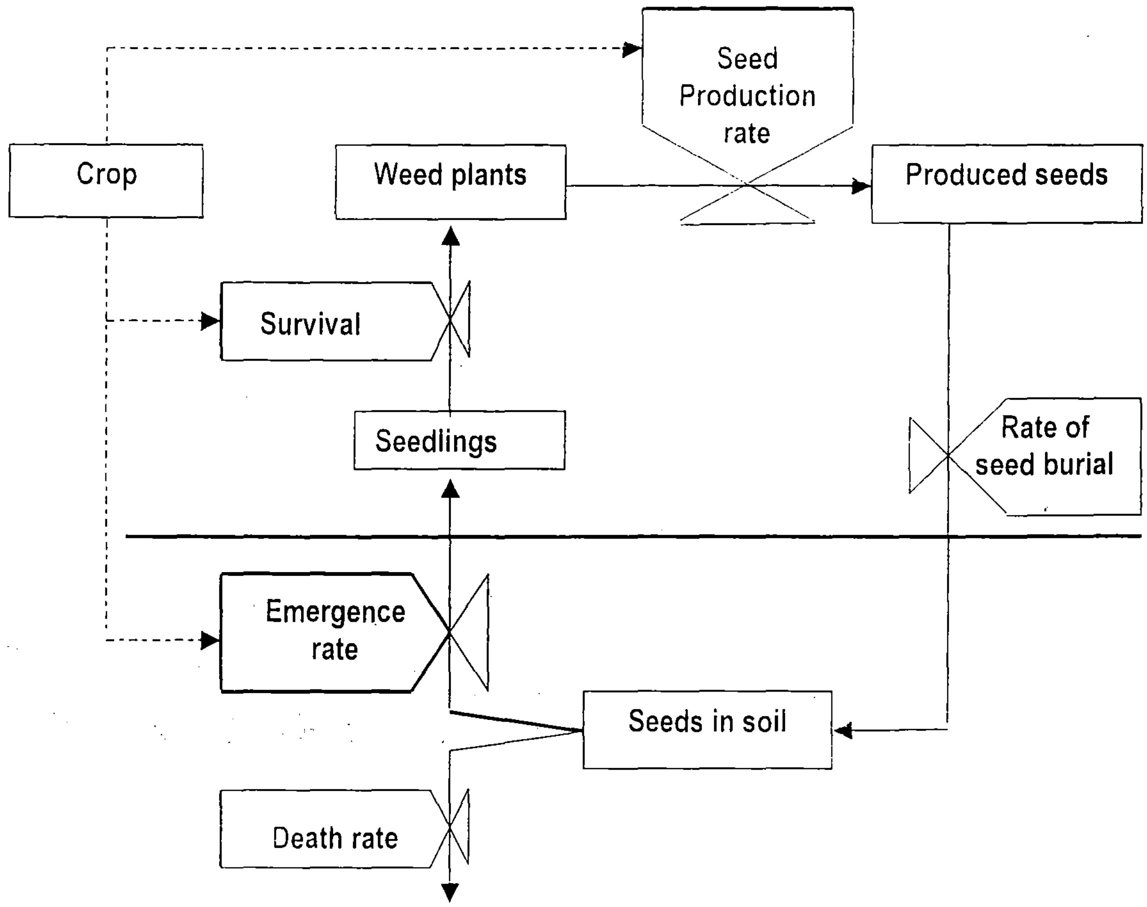

Figure 2.3. Schematic representation of a population dynamics model for weeds. Broken lines indicate processes where crop and weeds interact. (Adapted from Lotz, *et al.*, 1995)

2.4 Crop losses due to weeds

Weeds are considered the most persistent of all crop pests (Zimdahl, 1980). The major agronomic constraints limiting yields of any crop results from competition between weeds and crops for water, soil nutrients, space, and light. Competition is a dynamic process and can be understood, according to Kropff and Lotz (1992), from the distribution of the growth determining (light) or limiting (water, nutrients) resources over the competing species and the efficiency with which each species utilises them.

2.4.1 Weed-crop competition and interference

Many authors have described competition as a vital factor in the plant community. Brenchley (1920) emphasised this in her studies of weeds in farmlands, where she stated that, "It is impossible to sow a crop without the certainty that other plants will appear". A considerable volume of literature on weed-crop interactions has been accumulated over the last 40 years. Since Zimdahl's (1980) review on weed-crop, competition there has been a proliferation of research in this area. This barrage of research has helped to some extent, according to Cousens (1992), in developing an understanding of the nature of particular weed-crop interactions by providing information on:

1. yield losses in a given crop caused by a given population of a weed species,
2. the calculation of economic thresholds, and
3. improved weed control strategies.

The extent to which weed competition can reduce crop yield depends on species, density and duration (Cousens, 1992). Cousens (1992) stated that considerable variation exists among species of crops and weeds in their competitive abilities. A strong plant competitor, either a crop or weed retards the growth of other plants growing in association with it. Pavlychencho and Harrington (1934) studied plant competition. They examined the root development of weeds and crops in competition with each other under dry land farming. They observed that competition for water begins in the soil when root systems overlap in their search for water and nutrients. They concluded that weeds were strong competitors for water. Shaw (1982) reported that a plant of common ragweed (*Ambrosia artemisiifolia*) competes with corn, as it requires three times as much water as a corn plant. In other studies by Pavlychenco and Harrington (1934), it was mentioned that strong competitors tend to have larger embryos, early emergence and faster and taller growth.

Some weed scientists have differentiated between the types of competition as inter-specific (between plants of the different species) and intra-specific (between plants of the same species). When two plants interact, a number of processes may occur. According to Cousens (1992), this may lead to one, both or neither plant benefiting or suffering. Radosevich *et al.*, (1996) referred to these processes occurring as competition, allelopathy, parasitism, and commensalism. The term competition is strictly defined as the capture of limited resources by one individual at the expense of the other. As Cousens (1992) indicated, it was the first interference process that was postulated, and, as a result, the term 'competition' is often used synonymously with interference.

Despite this accumulation of information on weed-crop competition, Cousens (1992) critically analysed the fact that it has had less influence on the practice of weed control than anticipated. He stressed that more attention needs to be given to species comparisons, multispecies losses, effects of crops on weeds and the variability of yield loss among sites and years. Critical-period studies, he added, have had little effect on the understanding of competition. Competition develops through time, especially in relation to crop phenological development. He ended by establishing that research is needed in the area of comparative temporal development of weeds and crops and that a better understanding of this should lead to more efficient and environmentally sensitive weed control.

2.4.2 *Effects of weed interference on crop yield*

Weed infestations cause serious economic losses in many crops. In cereáls, for example barley, it was reported by O'Sullivan *et al.*, (1982) that yield loss (y) due to California thistle infestation was described by the equation:

$$Y = 0.42 + 7.6 \sqrt{x}$$

Where x is the number of Californian thistle shoots per square meter. A similar equation was tested by Hamman (1979) to estimate barley yield loss from a wild oat (*Avena fatua*) infestations:

$$L = ab\sqrt{x}$$

where L is the predicted yield loss (g/m^2); a is the weed-free yield (g/m^2), b is a competition index value, and x is the number of wild oat plants per m^2.

This equation gave a reliable estimate of yield losses with a competition index value, b, of 0.0230. Wilson and Peters (1982) found that barley yield was correlated with dry weight of wild oat plants at harvest. Most of the yield loss from weed competition was caused by a reduction in the number of barley tillers. However, in one year, they noticed that competition also led to smaller and fewer seeds per spike. They suggested that yield loss was due to replacement – type competition between two species.

Typically, loss in crop yield exhibits a proportional relationship with the abundance of weeds and the severity of interference (Cousens, 1985). Several authors have described the relationship between crop yield and weed density as sigmoidal (Zimdahl, 1980; Radosevich *et al.*, 1996) or quasi-sigmoidal with a biological threshold weed density below which no yield loss occurs. Cousens (1992) argues that such response curves are inappropriate and the statistics are not sufficient to describe yield losses. He emphasised that the appropriate approach should be a graphical presentation combined with non-linear regression. This should be used and less reliance placed on tables of means, hypothesis testing and multiple range tests. He further noted, based on work done on density responses, that only a small range of species in a small number of crops have been studied and there are few comparative studies of different weed species or different crops.

Weed impacts can change considerably with crop density, crop variety, relative time of emergence of weed and crop, fertiliser use and other factors. Cousens (1992) emphasised the paucity of research in these areas. He also stressed that predictions of yield loss caused by a single weed species in a crop are imprecise and possess considerable inaccuracies when trying to extrapolate from one (or more) experiments to a particular field in a particular year. Cousens (1992) also stated that few attempts have been made to study the effects of weed mixtures on crop yield. A few studies have been done on mixtures of two or three weeds, but mixtures of more species have not been studied in a systematic way.

A number of models have been developed for making realistic spray decisions. Spitters (1983), Coble (1985) and Wilson (1986) have all developed multispecies yield models.

2.5 The use of models for crop-weed interactions

Many models have been used to describe crop-weed interactions. Spitters and Aerts (1983) first introduced eco-physiological models for interplant competition involving light, water, and nutrient resources. Kropff and Lotz (1992) described the eco-physiological model as consisting of a number of crop growth models equal to the number of competing species. This model was referred to as a dynamic simulation model in which competition for light and water is simulated at the process level. Kropff and Lotz (1992) did an experiment with three weed species in three different sugar beet (*Beta vulgaris*) varieties using eco-physiological model predictions as a framework for the adoption of crop management strategies. The three sugar beet varieties were selected with differences in their leaf angle distribution, so that the variety chosen had the potential to suppress weeds. Leaves, which exhibited a more horizontal orientation, absorbed more light per unit leaf area of crop and significantly increased the death of late emerging weeds.

Spitters (1989) explained that the growth rate of a crop that is well supplied with water and nutrients is roughly proportional to its light interception. The rate of crop dry matter (DM) growth can be estimated from intercepted light and the average efficiency (E) with which the crop uses the intercepted light. Light interception is calculated from the incoming solar radiation (R) and the leaf area index (L) of the crop. The light flux penetrating the canopy decreases exponentially with the leaf area, so that the growth rate at time t is given by:

$$\Delta Yt = \{1 - \exp(-0.7\ L_t)\}\ 0.5\ R \times E$$

Where 0.7 is the light extinction coefficient and the factor 0.5 indicates that 50 % of the incoming solar radiation (R) is photosynthetically active. At optimum temperature, the light utilisation efficiency (E) does vary. However reports suggest that the radiation use efficiency (RUE) is about is 2.5 to 3g DM/MJ intercepted light for C_3 species and 4.5g DM/MJ for C_4 plant species (Sinclair and Muchow, 1999).

Kropff and Lotz (1992) mentioned that these models required too many inputs, such as dates of crop and weed emergence and weed densities in order to be useful for linking field observations to yield loss in agricultural practice. They suggested that a simple quantitative model be used to quantify weed infestation such as those developed by Cousens (1985) and by Kropff and Spitters (1991).

Empirical models have been developed to describe the responses of crop yield to one or more parameters such as weed density and the relative time of emergence with respect to the crop (Hakansson, 1983; Cousens *et al.*, 1987). Kropff and Spitters (1991) explained that, precise predictions of yield loss on the basis of early observations should be based on both weed density and the period between crop and weed emergence to determine the competitive relations between the crop and the weeds. Spitters and Aerts (1983) suggested that a relationship between relative leaf area and yield loss would be appropriate to predict yield loss rather than a relationship based on weed density. Kropff (1988) showed, using simulated data, that a close relationship existed between relative leaf area of the weeds and yield loss over a wide range of densities and relative times of weed emergence.

Spitters *et al.*, (1989) suggested an approach that was not worked out in experimental detail. The approach was based on a hyperbolic yield density function, in which the plant densities of each species are replaced by their LAI's monitored early in the growing season. Cousens (1985) concluded that a hyperbolic model gave the best fit for the available data in his review of weed density/yield loss models.

Kropff and Spitters (1991) mathematically derived an empirical model from the hyperbolic yield loss weed density relationship. The independent variables in this model were leaf area index (LAI) of a weed species as a fraction of the total LAI of all species. Density is often not an accurate measure of weed quantities in a field, as it does not account for the patchiness, size and emergence pattern of weeds (Parker and Murdoch, 1996). The relative leaf cover-yield loss model accounts for the effect of weed density, different weed flushes, as well as the period between crop and weed emergence. The model relates yield loss (Y_L) to relative leaf area (L_w expressed as leaf area weeds/leaf area crop + leaf area weeds) of the weeds shortly after crop emergence using a 'relative damage coefficient' q as the single model parameter:

$$Y_l = q\, L_w \,/\, 1 + (q-1)\, L_w$$

A further parameter was added by Lotz *et al.*, (1992):

$$Y_L = q\, Lw \,/\, 1 + (q\,/\,m - 1)\, L_w$$

Where m = maximum yield loss

Parker and Murdoch (1996) explained that the use of m may be needed to increase the accuracy of the yield loss prediction with weed species that, at high density, cannot result in total crop yield loss. Lutman (1992) suggested that measuring leaf area is a time consuming process, so that ground cover has to be used to replace leaf area parameters.

Spitters and Aerts (1983) reported that the competitive strength of a species is strongly determined by its share of leaf area at the moment when the canopy closes and inter-plant competition starts. In order to make precise decisions in weed management;

yield loss caused by the weeds has to be estimated as early as possible after crop emergence. The relative damage coefficient q depends on the ratio of the leaf area per plant of the crop and the weed (L_{ac}/L_{aw}). It is important to know how the relative area of weeds changes in the period between crop emergence and the moment when the crop canopy closes.

2.6 Effect of morphological and agronomic characteristics of crops on weed suppression

A reduced dependence on herbicides is desirable to reduce the cost of crop production, reduce environmental degradation and to impede the development of herbicide resistance. A large amount of research is now being conducted to develop integrated weed management strategies for agricultural producers. One component of such a strategy is to grow crops that are more competitive or to manipulate the crops' row spacing, plant population, and canopy influence to ensure that the crop-weed relationships are fully exploited. The growing of more aggressive crops could increase the density threshold values for weed control. This, perhaps, might improve the effectiveness of chemical treatments at lower application rates (Christensen *et al.*, 1994; Lemerle *et al.*, 1996 a, b) or mechanical control, with potential economic and/or environmental benefits (Paolini *et al.*, 1999).

One of the most important factors in a weed control program according to Johnson (1999) is the influence of the crop canopy. When the soil is fully shaded by the crop, sunlight is not available for weeds to establish and compete with the crop. This restriction of light is effective in manipulating emerging weeds (Verschwele *et al.*, 1994; Grundy *et al.*, 1997). Rapid development of the crop canopy may reduce reliance on herbicides to suppress weeds. There is evidence that these factors can be successfully manipulated to provide an enhanced competitive advantage for the crop, often at the expense of the weed flora. Different crops and crop cultivars can reduce weed biomass from 4 to 83 % during a full season of competition (Minotti and Sweet, 1981). Thus, the judicious manipulation of these factors can be a highly effective component of an integrated weed management system.

2.6.1 Effect of crops on weed suppression

Cereal crops: Cereals and pasture grasses are economically the most important plants in the world. They belong to the family Gramineae which, is one of the largest plant families. Included in this family are wheat, barley, oats, cereal rye, maize and others. FAO's first global cereal production forecast for 1999 was put at 1 850 million t. The cereal industry in New Zealand is largely based in Canterbury where about 93,114 ha of land is devoted to the growing of wheat, barley, oats and maize annually (Compendium of New Zealand Farm Production Statistics, 1999).

Cereals are very aggressive and are very competitive with many weed species. They have been referred to as "cleaning crops" by many researchers (Nelson *et al.*, 1991; Lemerle *et al.*, 1996 b) as their competitiveness allows them to suppress weeds. Differences in competitiveness among cereal cultivars have been studied extensively by Niemann (1992), Verschwele and Niemann (1992), Christensen (1995), Froud-Williams (1997), Lermerle *et al.*, (1996 b) and Seavers and Wright (1997). From these studies, the growth of weeds in barley and in wheat crops is negatively correlated with the early ground cover of the crop. Plant height of the crops also appeared to be an important factor determining the relative competitive ability of the crop.

Seavers and Wright (1995, 1997, 1999) conducted field experiments to study the weed suppression characteristics of different winter cereal cultivars and species. They studied two cultivars each of oats, barley and wheat using cleavers (*Galium aparine*) at five densities as the model weed. They found significant differences in the suppressive abilities of the crop species. Oats were the most suppressive, followed by barley and then wheat. There were also significant differences between the two wheat cultivars. The cultivar competitive ability was associated with a high overall leaf area, resistance to loss of tillers under competitive pressure, and a greater plant height.

Froud-Williams (1997) identified some of the traits that confer a greater competitive advantage to the crop. He identified these in his studies with various wheat cultivars and they included earliness of establishment, vegetative growth habit, tillering capacity, straw height, leaf canopy architecture, interception of photosynthetically active radiation, initial seed size and allelopathy. He concluded that attributes of traditional wheat cultivars enabled greater compensation of yield components in the presence of weeds. However, he suggested that yield attributes and those that confer competitiveness with weeds are not linked and could be selected for independently.

Verschwele and Niemann (1992) examined five winter wheat cultivars in terms of the possible influence of their morphology on weed suppression. Weed populations consisted of *Alopecurus myosuroides* (blackgrass) and *Myosotis arvensis* (field forget-me-not) sown between the rows, with rape (*Brassica napus*) sown into the wheat stands to simulate severe weed pressure. There was also some natural weed infestation with *Viola arvensis* (field pansy) and *Apera spica-venti* (loose silkybent). They found that light penetration was highly correlated with ground cover, plant height and stem weight of the crop and with weed growth. They concluded that consideration of selected morphological features was promising as an element for indirect weed control.

Brassica crops: The Brassicas grown in New Zealand cover a total area of 160,000 ha (MAF, 2000). Studies demonstrate that Brassica crops offer a good means of control in suppression of weed growth. Most Brassica species such as kales (*Brassic oleracea*), cabbages (*B. oleracea*), swedes (*B. napus*), rapes and others have a horizontal leaf morphology, which suppresses weeds quite effectively. Brassicas such as forage rape (*B. napus*) are fairly tall with a distinct main stem and branches bearing large, drooping, pale-green leaves (Langer and Hill, 1991) which provide a significant amount of shade to emerging weeds. Some turnip (*Brassica campestris*) cultivars grow very rapidly and mature very early offering greater competition with many weed species (Langer and Hill, 1991).

In field studies conducted by Al-Khatib *et al.*, (1997) weed suppression was evaluated when peas were planted after an autumn sowing of rapeseed (*B. napus*), white mustard (*B. hirta*), rye, or wheat had been incorporated into the soil in the spring. Weed suppression in the peas varied among the different preceding green manure crops. One month after sowing, the highest weed population was in peas after wheat and the lowest was in peas after rapeseed. Rye and white mustard suppressed early weeds relative to wheat by 25 and 30 % respectively. In greenhouse experiments, white mustard added to the soil reduced the emergence of shepherd's purse (*Capsella bursa-pastoris*), fireweed (*Kochia scoparia*) and green foxtail (*Setaria viridis*) by 97, 54 and 49 %, respectively. Rapeseed suppressed the emergence of shepherd's purse, kochia and green foxtail by 76, 25 and 25 %, respectively Al-Khatib *et al.*, (1997).

Field trials were conducted by Yadava and Narwal (1997) to assess the smothering effect on weeds of genotypes of *Brassica juncea* (Indian mustard), *B. napus* (rape) and *B. carinata*. The results indicated that some Indian mustard cultivars gave weed suppression of 70.4 – 76.6 %, which was attributed to the early growth of a broad dense foliage. Generally, all of the *B. napus* cultivars (Japanese and Canadian early – maturing, and Canadian late maturing) gave good weed suppression. This was because of their early development of broad leaves. Early–maturing varieties gave the best results with 82 % weed suppression, while the late–maturing cultivar Midas gave 78 % control. Because of slower growth, which enabled weeds to emerge before it, genotypes of *B. carinata* only gave a weed suppression of 44.6 – 65.6 %, although they also developed broad leaves.

Legume crops: Weed competition accounts for a considerable reduction in the yield of many legume crops. Many legume species have slow initial growth and rapid later development. Some legume crops such as field peas have some cultivars that have an open, sprawling growth habit and do not form a dense canopy, which can smother weeds. Other legumes such as narrow leafed lupins (*Lupinus angustifolius*) and green beans (*Phaseolus vulgaris*) are poor competitors. Therefore weeds, and weed control, are important especially during the early stages of growth. Some others lodge at an early stage and, for example in dry harvested peas, weeds grow through the canopy before harvest.

Over the past few years a limited number of studies on crop varietal influence on weeds have been carried out using legumes. The earliest study by Sweet *et al.*, (1974) compared the morphological influence of snap beans (*P. vulgaris*), sweet corn (*Zea mays*) and sweet potato (*Ipomoea batatas*) cultivars in suppressing yellow nutsedge (*Cyperus rotundus*). The results showed that, while neither root growth nor cultivar appeared to influence weed density, there was an almost perfect correlation between light interception (or shading) and weed suppression. One sweet potato cultivar (Green Mountain), competed successfully with weeds at three different locations by growing rapidly and intercepting 60 – 70 % of the light for nearly the entire growing season. Potato (*Solanum tuberosum*) cultivar (Katahdin) intercepted much less light and failed to compete with the weeds. The amount of branching, distance between the nodes and the continuous extension of vines were important in establishing and maintaining a tight canopy. However, the number of stems or leaflet size was of little importance in weed suppression. Some varietal conditioned influence on weeds was also shown by sweet corn, snap beans and acorn squash (*Cucumis* sp.) though in no case were the differences as pronounced as in potatoes and sweet potatoes.

Wortmann (1993) conducted a study to determine which morphological characteristics of beans (*Phaseolus vulgaris*) contributed to weed suppression and to assess the feasibility of breeding bean genotypes for improved ability to suppress weeds over three growing seasons. He found that the ability to suppress weeds was independent of bean growth habit but was related to leaf size. LAI and plant growth rate. Similar studies were conducted by Urwin *et al.*. (1996) using 12 cultivars of dry beans differing in plant canopy architecture and the amount of light intercepted. They used dry beans with a vine growth habit (Pinto 'D–84353') which gave a denser canopy and more yellow foxtail (*Setaria glauca*) suppression than Pinto 'RS–101' that had an upright growth habit. The growing season also influenced the plant canopy and late season weed emergence in their research. They observed no difference in weed suppression of different weeds among the cultivars.

Gane (1972) pointed out that the degree of competition that occurs depends upon a number of different factors. especially the weed flora present. In his study some relatively weak-growing weed species. such as *Spergula arvensis* (spurrey) and *Capsella bursa pastoris* (shepherd's purse) for example. were not very aggressive and could be tolerated in reasonable numbers without affecting a crop's performance. Other species such as *Avena fatua* (wild oats) did considerable damage to peas and is referred to as one of the greatest crop competitors of all.

2.6.3 Interaction of cultivar, row spacing and planting density on weeds

Malik *et al.*. (1993) indicated that cultivar selection. row spacing and the plant population density could enhance the crop competitiveness against weeds. All of these factors interactively can provide a non-chemical means of reducing the impact of weed interference on crop yields. Choice of cultivar has been shown to enhance crop competitiveness (Lotz *et al.*. 1991: Lermerle *et al.*. 1996 a: Paolini *et al.*. 1998). Taller and later maturing soybean (*Glycine max*) and white bean (*P. vulgaris*) cultivars have been shown to promote early canopy development and increase weed suppression (Swanton and Murphy. 1996). Increasing the seeding rate (ie. plant density) can also increase crop yield. At the same time. it aids weed suppression (Lawson and Topham. 1985: Teasdale and Frank. 1980: Teasdale. 1995. 1998). In barley. maize and other cereals it was found that higher yields were obtained when the crop was sown at narrower row spacings (Baldridge *et al.*. 1985). Narrower row spacing has the advantage of reducing the time required to achieve maximum leaf area. which may increase the crop's competitive advantage over weeds by facilitating competition for light and soil nutrients (Swanton and Murphy, 1996). Narrow row spacings are often used with more competitive cultivars e.g., taller cultivars that are better suited to higher plant densities (Swanton and Murphy, 1996).

Stanojevic *et al.* (1996) reported decreases in weed biomass by increasing maize population using seven densities. Maize (*Zea mays*) is a tall growing, vigorous and highly competitive plant that produces large amounts of above ground vegetative tissue. Competing weed species only flower and form reproductive organs with difficulty (Moore *et al.*, 1994). At high plant densities maize is a good competitor with many weeds. The relative competitive ability of maize can be enhanced by increasing plant density (Tollenaar *et al.*, 1994). However, at low plant densities the crop can suffer considerable yield losses due to weed competition. Rahman (1985) reported losses of greater than 30 % in maize in competition with weeds. Stanojevic *et al.*, (1996) pointed out that a lower crop stand provides more free space for weed development thus weed stands are increased. As plant population increased maize LAI increased and light transmittance to the soil decreased. Hence, the growth and development of weeds is suppressed (Gallo and Daughtry, 1986; Tetio-Kagho and Gardener, 1988 and Teasdale, 1995).

Replacement experiments conducted in São Paulo, Brazil by Christoffoleti and Victoria (1996) to describe the competitive interaction between corn and pigweed (*Amaranthus retroflexus*) showed that the influence of plant density and the proportion of a species in a competition study are very important when describing competitive interactions. Studies by Teasdale *et al.*, (1998) to determine the optimum population and row spacing for maize production and for suppressing velvet leaf (*A. theophrasti*) growth and production, showed that reduced velvet leaf seed production was correlated with a lower positioning of plants in the maize canopy and reduced light availability. Their results suggested that higher maize populations could aid in integrated weed management by reducing weed seed production and limiting the build up of weed populations

Field trials in India by Singh *et al.*, (1997) demonstrated that by increasing the plant populations in maize to 83,333 plants/ha (60 x 20 cm spacing), the uptake of nitrogen, phosphorus and potassium was increased. However, grain number/ear and test weight increased with decreased plant density.

Westgate *et al.*, (1997) working with two maize hybrids of contrasting canopy architecture and potential biomass production showed that early canopy closure was achieved by using a combination of narrower row spacings and greater plant population densities (PPD) than those used by local producers. It was recognised that maximum interception of incident PAR and total PAR intercepted from sowing increased with PPD. Murphy *et al.*, (1996) explained that increased PPD resulted in increased LAI and reduced photosynthetic photon flux density (PPFD) transmittance, which would reduce the ability of weeds to compete for light.

Beans have been shown to compete better with weeds in narrow row spacings from 25 to 50 cm by Teasdale and Frank (1980) because of leaf canopy shading. They have also shown that seed yields could be increased in addition to suppression of weeds when they were grown in 46 cm rows rather than in 91 cm rows. Beans were grown in rows of 15, 25, 36, 46 and 91 cm apart. The spacing between individual plants in the row was increased as the distance between the rows was decreased, to give a constant density of 43 plants/m^2 and this resulted in reductions in the weeds/m^2. Trials by Maiti *et al.*, (1997) found that pigweed (*Amaranthus retroflexus* L.) and fathen caused significant yield reductions in beans when they were grown in narrow rows. Weise (1985) also found a significant yield reduction in beans with 3.9 weeds/m^2 when grown in wide rows.

Rao *et al.*, (1997) found that increasing the plant population of beans from 2.0 to 5.0 x 10^5 plants/ha significantly reduced both the number of weeds and weed DM/m^2 and increased crop yield per hectare. McKenzie *et al.*, (1989) in studies on the relationship between lentil (*Lens culinaris*) crop population and weed biomass production found that the reduction in weed DM at higher lentil populations was primarily due to increased light interception by the lentils. Crop canopies of lentil, over three growing seasons, intercepted a maximum of 95 % of the incident solar radiation at a LAI of 7. Transmissivity readings showed a significant reduction in the transmission of radiation through the crop canopy at populations of more than 200 plants/m^2.

Marx and Hagedorn (1961) found that high populations of peas (148 plants/m^2) markedly reduced weed development compared with lower populations. As plant population increased and row spacing was narrowed, weed growth decreased. The effect of population was more pronounced than the effect of row spacing (Marx and Hagedorn , 1961). White and Anderson (1974) also found that as plant population increased from 36 plants/m^2 to a population of 371 plants/m^2 in peas weed incidence was decreased.

Increasing plant density, according to Nichols *et al.*, (1981), almost invariably results in a reduction in yield per plant (either of total biomass, or of economic yield), due to intra-specific competition for light, moisture and nutrients. In addition to reducing plant biomass by increasing plant density, the partitioning of DM may be modified and the time and spread of maturity may be affected.

Herbert (1977) found that plant density and row spacing can be important factors in weed suppression. In his experiments with dense lupin (*Lupinus angustifolius*) populations, effective weed suppression of yarrow was obtained when conventional herbicides were ineffective. Narrow rows and higher densities appeared to be more desirable. This was based on obtaining rapid canopy closure and the control of perennial weeds. Increasing crop density effectively shortens the weed free period necessary after crop emergence and thus lower rates of herbicides can be used (Gane, 1972).

2.7 Conclusions

Weeds continue to have major impacts on crop production in spite of efforts to eliminate them. Regardless of developments in weed control technologies, changes in weed abundance continue to follow changes in farming practice. It is widely accepted that successful programs in which weed control is achieved are usually through the use of chemicals. Concomitant with such use comes increasing public concern about associated environmental effects.

There has been renewed emphasis on long term weed management and the integration of a range of methods of weed control. At the centre of this approach is the need to understand the dynamics of weed communities and their populations. Recent research by scientists and conservationists have stressed new techniques that could be incorporated into the farming systems to reduce the adverse effects of weeds and at the same time minimise dependency of herbicides. Kropff and Walter (2000) emphasised that the challenge today is to develop integrated crop management systems in which preventative measures (reduction in weed effects through crop management) are used first and are followed by precision control. It has been suggested that an integrated approach offers the best alternative to weed management and that practices that give the crop a competitive advantage in competing with weeds should be exploited (Bridgemohan, 1993). These could include one or more of the following, which will be the focus of the research to be presented in this thesis:

1. *Competitive crops* - within a crop species, cultivars may differ in their competitiveness with weeds based on their emergence, leaf-area expansion, light interception, canopy architecture and leaf-angle shape and size. These differences may aid in the suppression of weed species. Considerable work, reported by Seavers and Wright (1999) and others, show that cereals such as oats, barley and wheat all have the potential, based on their competitive growth habits, to suppress weeds. Tollendaar *et al.*, (1994) highlighted the need for research in crop-weed interactions, including the impact of the relative competitive ability of the crop during various phases of development on weed growth. This information would assist in the development of an effective integrated weed management system.
2. *Optimum plant population* – Cereals and vegetable crops can compete with weed growth if they are established at an optimum plant density that allows them to more effectively usurp resources. Reducing the light incidence by 50 % or more may reduce weed occurrence. Manipulating the intra- and interow spacings to increase crop plant densities can also reduce weed problems.
3. *Smother crops* - These crops are quickly established and usurp the resources that weeds would otherwise use. The suppression of weeds may be through both competition (resources) and/or by allelopathy.

Despite the fact that integrated weed management systems are considered technologically sound, the social and environmental advantages, as well as the economic costs associated with the practice need to be ascertained. Farmers need to be convinced of the economic viability of the system for the technology to be adopted. A comparative study on the effects of crop morphology and increasing crop density on the distribution and suppression of weeds may provide valuable information for incorporation into an integrated weed management system.

Chapter 3

Weed suppression and crop yield effects of different densities and of crops canopy architectures[1]

3.1 Introduction

In modern agricultural systems, weeds are still predominantly controlled by herbicides despite growing environmental concerns of ecological problems and the contamination of ground and surface water. Ecologically based weed management strategies have been suggested (Liebman and Dyck 1993; Buhler, 1999; Liebman and Davis, 2000) to reduce the need for herbicides. Crops and weeds compete for the resources of light, water and nutrients and ecologically based weed control strategies exploit the competitive ability of crops in suppressing weed growth. The competitive ability of the crop can be attributed to early emergence, seedling vigour, high rate of leaf expansion, rapid formation of a dense canopy and tall stature. An understanding of these weed-crop competition mechanisms and how they impact upon the population dynamics of a weed is essential in ecologically – based weed management.

The crop has an important role to play in a weed control strategy since crop plants can suppress weed development in the same way as weeds can interfere with crop growth. Putnam (1986) reported that the intensity of weed suppression depended principally on the morphology and rate of crop growth, but allelopathy can also be important. Plant density, choice of crop, time of sowing and other aspects of crop production may also influence the level of weed suppression (Christensen *et al.*, 1994). For example, potato (*Solanum tuberosum*) has a vigorous growth habit that smothers weeds (Sweet, 1974 a).

Early establishment in all crops is important to achieve maximum weed suppression (Froud-Williams, 1997). Weeds grow unhindered when crop cover is poor, as there is a lack of crop competition. Decreased light transmission through the leaf canopy of crops planted in closely spaced rows, or at high populations, may considerably suppress weed growth and development (Teasdale, 1995). Greater weed

[1] A version of this paper has been submitted to *Agronomy New Zealand*

growth, in addition to contributing to crop yield losses, may exacerbate future weed problems as a consequence of seed production (Grundy *et al.*, 1999).

Research on weed suppression by crop manipulation has increased during the past few years. Studies exploring crops' competitiveness against weeds have to date, centred on small grain cereals. There is little information for vegetable or legume crops. Grundy *et al.*, (1999) highlighted the dearth of information on the competitive ability of different crops with respect to their weed suppressing traits. Teasdale (1995) and Seaver and Wright (1997) acknowledged the need for studies of the differential response of important weed species to high crop population. In Canterbury, Herbert *et al.*, (1978) and McKenzie *et al.*, (1986) reported weed suppression by increasing plant population in narrow – leafed lupins (*Lupinus angustifolius*) and in lentils (*Lens culinaris*) respectively.

Based on the hypothesis that varying crop morphology may affect weed development and that increased crop density may lead to decreased weed density by decreasing the time to canopy closure, which would decrease the critical period for weed control and ultimately limit or negate the need for herbicides, the following experiment was conducted to test:

a) the effect of 6 morphologically different crops on the suppression and emergence of a natural weed infestation in the absence of any other control measures;

b) whether varying the density of morphologically different crops affected their ability to suppress weeds and had any effect on crop productivity; and

c) to identify which crop morphological characteristics are desirable for suppression of weed growth.

3.2 Materials and Methods

3.2.1 Experimental site and preparation

The experiment was conducted on Paddock D2 at Lincoln University, New Zealand at 43 ° 38 'S. It was sown into a Templeton silt loam (New Zealand Soil Bureau, 1968). The site has a slight northward slope. The area had previously been in a predominantly white clover (*Trifolium repens*) pasture for five years. However, preparatory soil cores revealed that twin cress (*Coronopus didymus*) dominated the soil weed seed bank based on weed seed count estimates. A MAF soil quick test, prior to sowing showed the site was of medium fertility with a pH of 5.3. One dressing of superphosphate (0-9-0-12) at 250 kg/ha was broadcast onto the trial area in the second week after sowing. The field was prepared using standard cultivation practises of ploughing, harrowing and rolling. Crop seeds were drilled into a fine firm seedbed of adequate moisture using a Öyjord cone seeder.

3.2.2 Experimental design

A randomised complete block design was used with three replicates. To give a wide range of variation in weed species composition and densities, six morphologically different crops were sown. There were a total of 72 plots with crops and two no crop controls at each sowing. This gave a grand total of 78 plots. The crop treatments were: forage rape (*Brassica napus* cv. Giant rape), narrow leafed lupin (*Lupinus angustifolius* cv. Fest), and rye (*Secale cereale* cv. Petkusier) in the first sowing which was on 8 September 1999 (early spring). In the second sowing which was on 4 November 1999 the crops were maize (*Zea mays* cv. Janna), dwarf French beans (*Phaseolus vulgaris* cv. Elita), and turnip (*Brassica campestris* cv. Green globe).

Each of the crops was sown at four densities (0.5, 1.0, 2.0 and 4.0 x the optimum plant population) as shown below:

Forage rape (cv. Giant rape)	–	(25, 50, 100 and 200 plants/m^2)
Narrow leafed lupin (cv. Fest)	–	(50, 100, 200, 400 plants/m^2)
Ryecorn (cv. Petkusier)	–	(125, 250, 500, 1000 plants/m^2)
Maize (cv. Janna)	-	(6, 12, 24, 48 plants/m^2)
Beans (cv. Elita)	–	(25, 50, 100, 200 plants/m^2)
Turnips (cv. Green globe)	–	(25, 50, 100 and 200 plants/m^2)

Plots were 10 m long x 4.2 m wide. Sowing depth varied with crop. The larger seeded crops (lupin, maize, ryecorn and beans) were sown at 4 - 5 cm and the smaller seeded crops (forage rape and turnips) were sown at 2 cm. There was 15 cm between rows.

Before sowing the late sown crops the plots to be sown were sprayed with one application of glyphosate at 150 ml/ha using a mounted tractor drawn sprayer. Seeds were then direct drilled into a clean seedbed at the above rates.

3.2.3 Crop protection

To control an infection of leaf rust (*Puccinia graminis*) on the ryecorn the fungicide Tilt® 250 EC (Propiconazole) was used. It was applied at 500 ml/ha in 200 l/ha of water using a knapsack sprayer on 7 December 1999 when the symptoms were identified on the high-density plots.

An application of the insecticide Lorsban® 48 EC (Chloropyrifos) was applied to the forage rape to avoid the spread of the aphid, *Lipaphis erusimi*. This was done on 24 November at 500 ml/ha in 237 l/ha of water using a tractor-mounted sprayer.

3.2.4 Measurements

Weed measurements: From canopy closure on, plots were destructively sampled using a $0.25 m^2$ quadrat to measure the dry matter (DM) production of the crop and the weeds. One $1 m^2$ quadrat was placed in the centre of each plot and was left for sampling at final harvest. Weeds were sorted by taxa (species or genus, depending on their similarity) (see Chapter 5). Uncommon taxa were pooled and their total dry weight recorded. All samples were cut with hand clippers to ground level and were dried to constant weight at 70 °C for 24 h in a forced draught oven.

Crop measurements

Within canopy environment: Irrigation was applied once to the trial when the soil moisture level fell below 50 % of field capacity. This was applied using an overhead sprinkler (Bisley – hand shift). For the rest of the growing season the trial was rain-fed. Temperatures within the canopy on randomly selected plots, of each of the different treatments were monitored at hourly intervals daily by means of HOBO data loggers (Onset, Bourne, MA). One probe was placed into the canopy, two in the soil under the canopy and another about 20 cm above the canopy. Solar radiation levels were obtained from the Broadfields Meteorological Station located about 1.0 km from the experimental site.

Crop parameters: Plant height was recorded for the first 8 weeks from randomly selected plants in the plots. Leaf area was measured twice by destructive sampling, to derive leaf area index (LAI). It was also measured weekly non-destructively from week 4 after sowing to final harvest using a LICOR LAI 2000 Plant Canopy Analyser. Four readings were taken randomly above and beneath the crop canopy from each plot during cloudy periods. Crop DM, LAI and amount of radiation transmitted through the canopy (T_i) were recorded starting 60 days after sowing (DAS) and continued fortnightly until final harvest. The amount of photosynthetically active radiation (PAR) intercepted was calculated from Szeicz (1974):

$$S_a = F_i \times S_i \times 0.5 \text{........ Equation 3.1}$$

where the S_a is the PAR and S_i is the total incident solar radiation, which was calculated from the Broadfield Meteorological station from the time of crop emergence to crop physiological maturity.

The proportion of radiation intercepted (F_i) by the canopy was calculated according to Gallagher and Biscoe (1978):

$$F_i = 1.0 - T_i \text{..............Equation 3.2}$$

Transmittance through the canopy was fitted to a nonlinear sigmoid regression (Teasdale, 1995):

$$Y = 1 / (1 + (X/c)^b) \text{......Equation 3.3}$$

where the coefficient b is the rate of decline of light transmittance with time once the canopy begins to close and c represents the day when light transmittance is reduced to 50 % of that of incoming radiation (when X = c, Y = 0.5).

The radiation use efficiency (RUE) for each crop was obtained as the slope of regressions of crop DM on the intercepted PAR from seedling emergence to maturity.

Total crop DM samples were taken using a 0.25 m^2 quadrat at fortnightly intervals. At final harvest, DM production was measured from a 1 m^2 area. Plant samples were clipped, along with the weeds, to ground level and oven dried to constant weight at 70 °C.

Yield and yield components were measured for the grain crops (lupins, ryecorn, maize and dwarf French beans). The seed yield, harvest index (HI) and total biological yield and components of seed yield were determined from an undisturbed central area 1 m^2 within each plot. Samples were hand harvested and plants were mechanically threshed and cleaned after they were air dried to constant weight in a drying room. Final harvests were taken when crops reached a moisture content of 15 - 18 %.

3.2.5 Analysis

All data were subjected to analysis of variance (ANOVA). Means were separated at the 5 % level of significance using least significance difference (LSD) for crop and population main effects and the crop x density interaction. Since the experiment was conducted using 6 different crop species, and since the interactions were in most cases significant only interaction means are presented. The experiment was analysed using GENSTAT 5.4.1(1997) and MINITAB 11.12 (1996) statistical packages. Orthogonal contrasts were performed between different crop type combinations.

3.3 Results

3.3.1 Environment

Climatic measurements were obtained from the Broadfields Meteorological Station, Lincoln University. Climate data during the trial period did not vary greatly from previous years. Rainfall was adequate and timely for crop growth throughout the growing season. From September 1999 to April 2000, rainfall was 82 % of the long term mean. However, in December 1999 with decreasing soil moisture, because of reduced rainfall, 30 mm of irrigation was applied to maintain soil moisture near field capacity.

Minimum temperatures were very low (9 °C) particularly in November 1999 compared with the long – term means. The mean monthly solar radiation received over this period was (538 MJ/m^2). This was higher than the long-term mean of 502 MJ/m^2 (Figure 3.1.). The average photoperiod of 15.6h/day was well within the range favourable for growth and development of the crops. Appendix 2 shows the temperatures from the data loggers for air, within canopy and soil. Within canopy and soil temperatures were always higher than the air temperatures.

3.3.2 Plant population

Although all seed was sown by the same seed drill there were differences in plant population. Established plant populations were higher than expected for lupin and turnip. The lower plant populations of rape and maize were also higher than expected. However, the higher populations of rape and maize as well as all densities of ryecorn and bean were lower than anticipated. Table 3.1 shows the different plant populations (plants/m^2) for 0.5, 1.0, 2.0 and 4.0 x optimum population (actual and expected).

3.3.3 Dry matter production

Total crop dry matter at harvest: Crop species had a large effect on the total dry matter (TDM) productivity at 60 DAS (Table 3.2) and at final harvest (Table 3.3) ($p < 0.001$). At 60 DAS turnip produced the highest TDM (396.6 g/m^2) of all the crops followed by maize (213.2 g/m^2), lupin (174.4 g/m^2), ryecorn (121.4 g/m^2) and bean (68.8 g/m^2). However, by final harvest the highest TDM was produced by maize, lupin, ryecorn, bean and turnip at 20.3, 11.5, 5.7, 4.5 and 1.3 t DM/ha respectively.

Increasing the plant population significantly increased TDM at 60 DAS ($p < 0.001$). There was however, no significant density effect at the final harvest. At 60 DAS DM increased with increased plant population (0.5 to 4.0 x optimum population) for lupin from 91.2 – 259.6 g/m^2, ryecorn from 70.0 – 185.0 g/m^2, and maize from 93.0 – 343.0 g/m^2. There were some discrepancies in bean and turnip where DM decreased from 1.0 – 2.0 x optimum population in bean and from 0.5 – 1.0 x optimum population in turnip. At final harvest crop DM increased with increased plant population only for turnip. There was some variability in DM for lupin, which decreased with increased plant population (0.5 to 4.0 x optimum population) from 12.1 to 11.2 t DM/ha. The maximum DM was achieved at 2.0 x optimum population for rape (9 t DM/ha), 1.0 x optimum population for maize (28 t DM/ha) and 4.0 x optimum population for ryecorn (6.3 t DM/ha). There was a significant crop x density interaction at 60 DAS ($p < 0.05$) and at final harvest ($p < 0.001$).

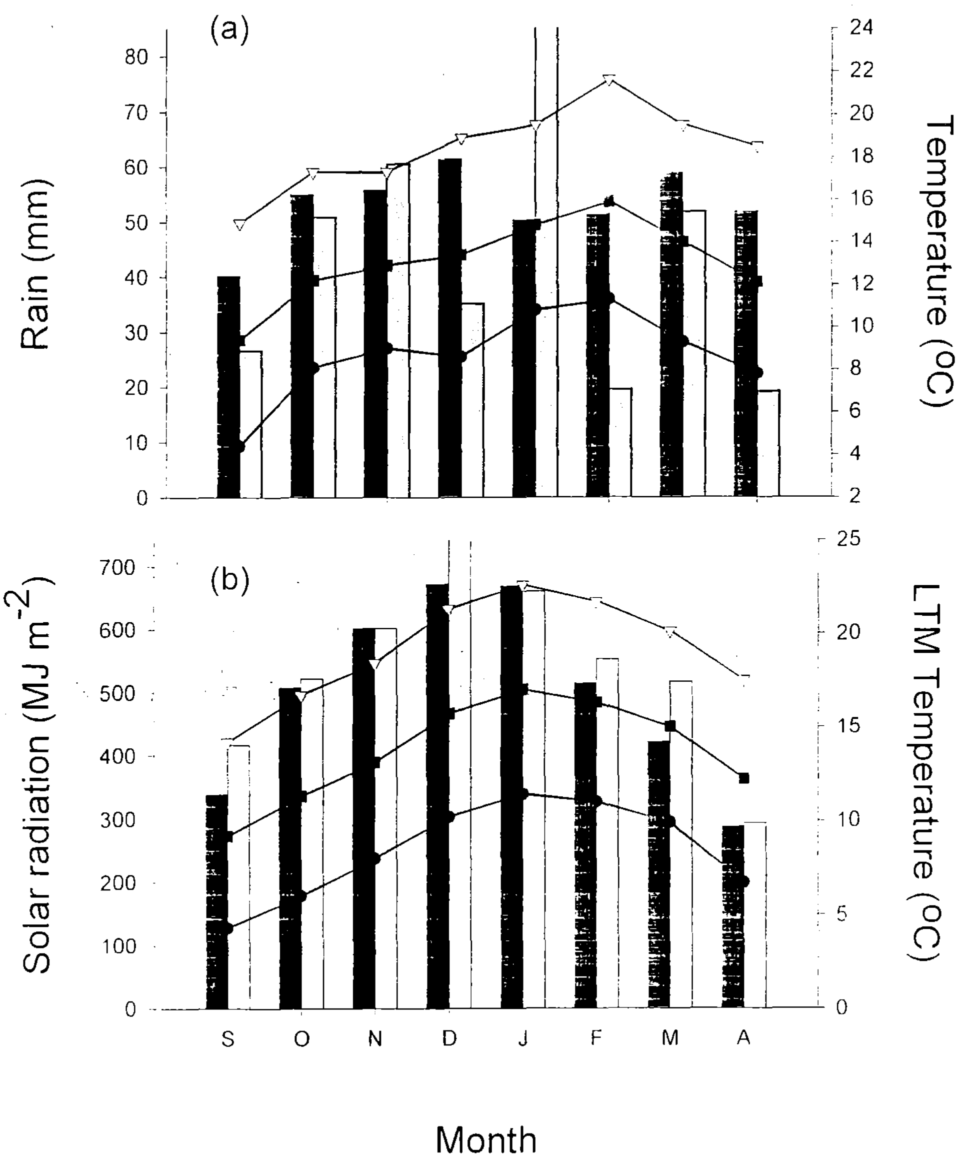

Figure 3.1. Weather pattern for the September to April experimental period, 1999-2000 and the long term means (LTM) from Broadfields Meteorological station. (Bars: – (■) – LTM, (□) – 1999-2000). (●) – Min., (▽) – Max., (▪) – Mean Temperatures.

Table 3.1: Expected number of plants/m^2 and the actual plant establishment at 60 days after sowing.

Crop treatment	Number of plants m^{-2}	
	Expected	Actual
Narrow leaf lupin[1]	50	58
	100	126
	200	224
	400	441
Ryecorn[1]	125	69
	250	141
	500	309
	1,000	810
Rape[1]	25	30
	50	63
	100	91
	200	181
Maize[2]	6	7
	12	14
	24	23
	48	40
Beans[2]	25	14
	50	33
	100	71
	200	136
Turnip[2]	25	44
	50	57
	100	139
	200	234

[1]and [2] indicate early and late sown crops respectively.

Crop duration and dry matter accumulation: Figure 3.2 a –3.3 a illustrates the changes in DM over the growing season for the different crops. There was a considerable effect of crop treatment on the time to harvest maturity. The DM production increased until harvest maturity for most crop treatments. Increasing the plant population resulted in more rapid DM accumulation.

For the early sown crops (Figure 3.2 (a)), lupin showed a steady increase in DM accumulation until 140 DAS for all plant populations and then decreased. The highest DM was at 2.0 x optimum population (19.5 t DM/ha). Similar trends were observed in ryecorn and rape which both increased steadily achieving their maximum DM productivity at 1.0 x optimum population (195 and 120 DAS respectively). In the late sown crops, both maize (which produced the highest crop DM overall) and beans reached their highest maximum dry matter production at 2.0 x optimum population (140 DAS) (Figure 3.3 (a)). Maize however, showed some variability in DM accumulation over time, increasing steadily up to 110 DAS, decreasing at 120 DAS, rapidly increasing to 130 DAS and declining until final harvest at 190 DAS. Turnips achieved their highest DM at 140 DAS at 4.0 x optimum population (736 g/m^2) (Figure 3.3. (a)). The DM production of ryecorn declined at about 120 and 150 DAS at 2.0 and 4.0 x optimum populations. Ryecorn had the longest duration of all the crops at 210 DAS

Total weed dry matter at harvest: At 60 DAS there were significantly less weeds under turnip than under any other crop treatments ($p < 0.001$) (Figure 3.3 b and Table 3.2). Turnip weeds accounted for 5 % (5.2 g/m^2) of the total weeds produced under crop treatments followed by ryecorn (8.3 g/m^2), maize (11.7 g/m^2), lupin (15.7 g/m^2), bean (23.5 g/m^2) and rape (40.0 g/m^2). At final harvest, turnip also had the lowest weed DM (0.58 g/m^2) followed by ryecorn, maize, lupin, rape and bean which accounted for 8, 9, 21, 27 and 34 % of the total weed DM production in the crop treatments respectively. Figures 3.6 – 3.8 illustrates the relative proportions of TDM of crop and weed.

There was no significant difference in weed DM between the early and late sowing at 60 DAS and at final harvest based on orthogonal contrasts (Table 3.4). The orthogonal contrasts did reveal significant differences between lupin and bean (297.0 vs. 494.0 g/m^2) at final harvest ($p < 0.05$) and between rape and turnip at 60 DAS (160.0 vs. 20.7 g/m^2) ($p < 0.01$) and at final harvest (385.0 vs. 2.3 g/m^2) ($p < 0.001$) when the influence of plant population was removed. The ryecorn and maize, and lupin and bean comparisons were not significantly different.

There were significant density effects at 60 DAS among the different crop treatments ($p < 0.05$) (Table 3.2). Weed DM at 60 DAS in the 0.5 x optimum population was highest for ryecorn, bean and turnip and was lower at the other plant populations. However, there were some exceptions. In lupin and maize weed DM was highest at 1.0 x optimum population and decreased with increased plant population from 1.0 to 4.0 x optimum population (36.6 – 3.3 g/m^2 and 30.2 - 2.3 g/m^2 in lupin and maize respectively from 1.0 – 4.0 x optimum populations). Weed DM in rape increased from 0.5 to the 1.0 x optimum population and 2.0 to the 4.0 x optimum population by as much as 31 g/m^2.

Significant density effects were also observed at final harvest among crop treatments ($p < 0.001$) (Table 3.3). There was a general decrease in weed DM with increased crop density for lupin (from 125 – 7.0 g/m^2), rape (189.0 – 26.0 g/m^2), ryecorn (51.0 – 18.0 g/m^2), bean (397.0 – 12.0 g/m^2) and maize (106.0 – 0.0 g/m^2) from 0.5 – 4.0 x optimum populations at final harvest. There was also a significant crop x density interaction between the different crop types tested at 60 DAS and at final harvest ($p <$ 0.01 and 0.001 respectively) (Table 3.2, 3.3).

Overall, turnip reduced weed cover by more than 95 % at all plant populations (Figure 3.5). Maize, lupin and ryecorn also suppressed most of the weeds present particularly at high crop densities. Bean and rape were less effective at suppressing weeds. Weed DM was highly negatively correlated with crop DM at 0.0, 0.5, 1.0, 2.0 and 4.0 x optimum populations ($p < 0.01$) at final harvest from 567.1 – 12.0 g/m^2 and 904.6 – 26.0 g/m^2 for bean and rape respectively (Figure 3.4).

Bean was the least competitive of the crops and was virtually eliminated by the weeds at 0.5 x optimum population where weed coverage was over 50 %. In all the crops except for turnip, increased crop population from 0.5 to 4.0 x optimum population reduced weed DM yield.

The leaf area index (LAI) was strongly negatively correlated with weed DM in lupins ($r^2 = -0.770$) and maize ($r^2 = -0.609$) (Figure 3.11). This relationship showed there were increased weed levels at lower LAI's at lower plant populations.

Weed dry matter accumulation: Weed DM increased gradually with successive harvests for some of the crop treatments. At sequential harvests lupin at the 0.5, 1.0 and 2.0 x optimum populations showed a general increase in weed DM with a few exceptions at the various harvests (Figure 3.2, (b), 3.3, (b)).

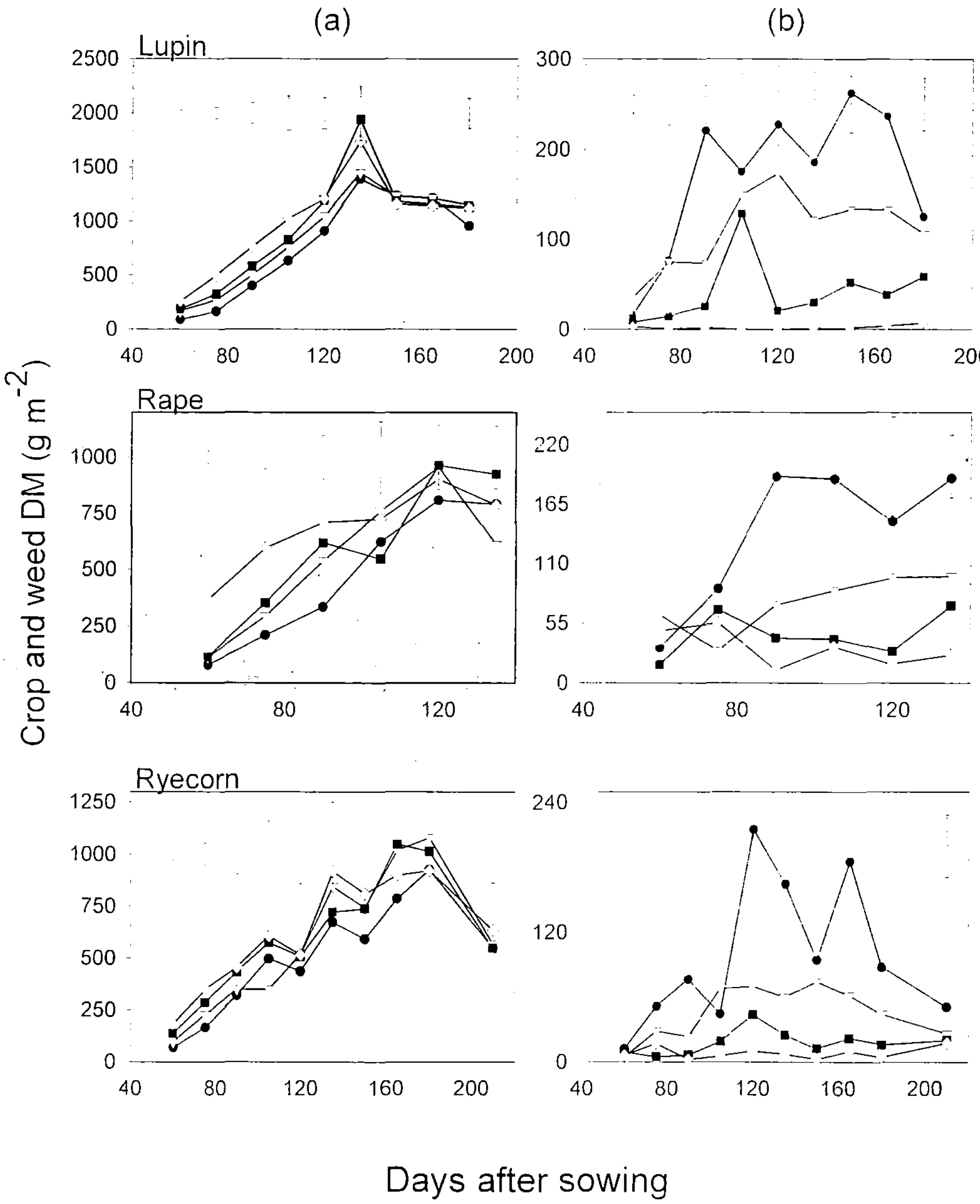

Figure 3.2. The dry matter accumulation of the early sown crops (a) crop and (b) weed at 0.5 (●), 1.0 (∇), 2.0 (■), and 4.0 (◊) x optimum population over the growing season 1999/2000. Bars indicate SEM

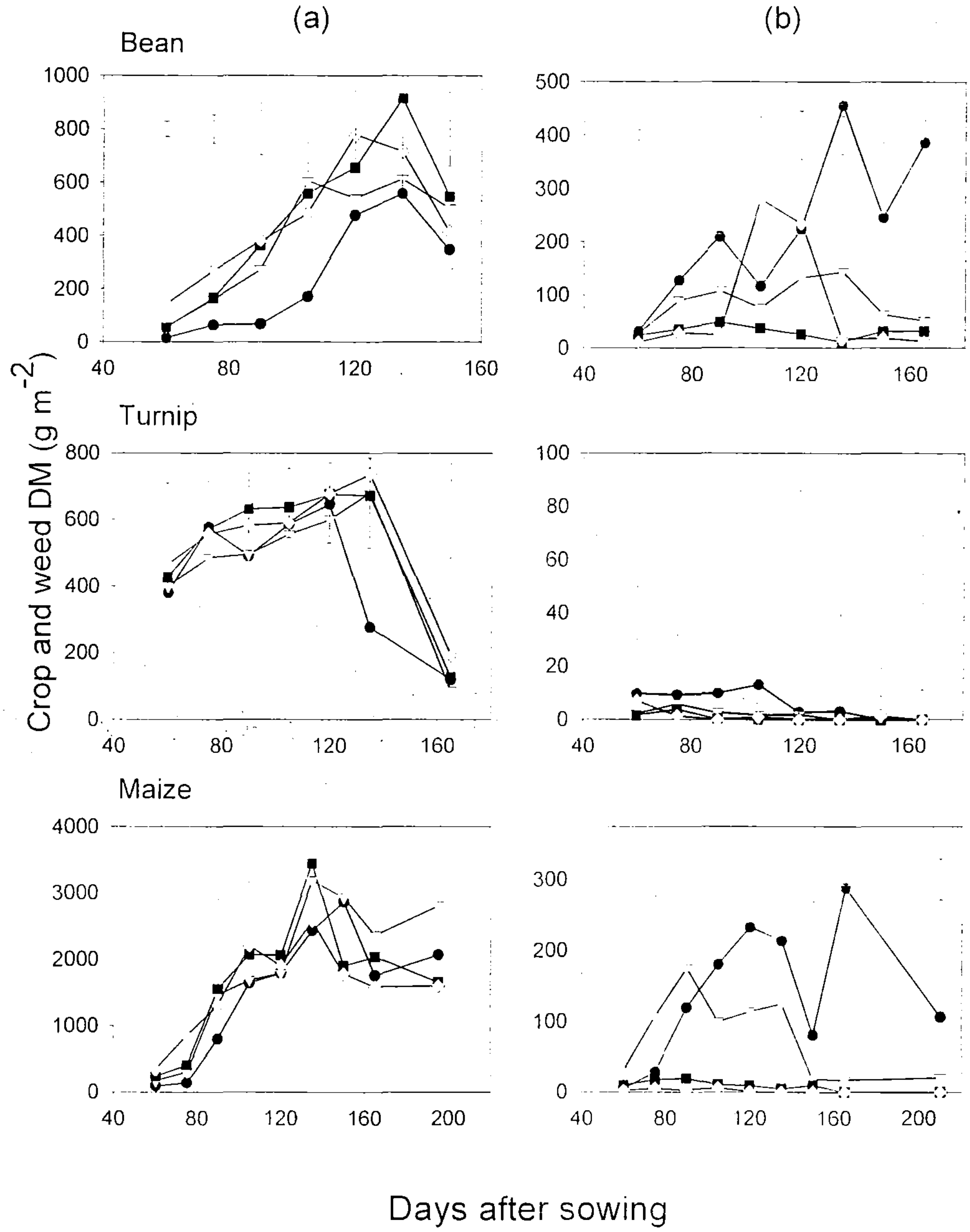

Figure 3.3. The dry matter accumulation of the late sown crops (a) crop and (b) weed at 0.5 (●), 1.0 (∇), 2.0 (■), and 4.0 (◊) x optimum population over the growing season 1999/2000. Bars indicate SEM

Table 3.2. The interaction between crop density and species on crop and weed dry matter at 60 DAS (g/m2) in the 1999/2000 growing season.

Crop dry matter			Weed dry matter		
Crop density	Sowing 1	Sowing 2	Crop density	Sowing 1	Sowing 2
	Lupin	Bean		Lupin	Bean
0.5	91.2	16.5	0.5	15.9	31.9
1.0	165.3	59.1	1.0	35.6	27.4
2.0	181.5	56.0	2.0	8.1	23.8
4.0	259.6	143.6	4.0	3.3	11.0
	Rape	Turnip		Rape	Turnip
0.5	80.0	380.0	0.5	32.0	9.8
1.0	113.1	313.6	1.0	63.0	2.2
2.0	115.2	427.0	2.0	17.0	1.6
4.0	366.0	466.3	4.0	48.0	7.1
	Ryecorn	Maize		Ryecorn	Maize
0.5	70.0	93.0	0.5	12.4	4.5
1.0	94.7	174.0	1.0	5.0	30.2
2.0	136.4	243.0	2.0	9.4	9.8
4.0	185.0	343.0	4.0	6.3	2.3
Significance					
Crop	***			***	
Density	***			*	
SEM	28.7			10.1	
CV (%)	26.1			100.3	

NS, non-significant; *, P < 0.05; **, P < 0.01; ***, P < 0.001; ND, not determined. Crop density = 0.5, 1.0, 2.0, and 4.0 x optimum population.

Table 3.3. The interaction between crop density and species on crop and weed dry matter at final harvest (g/m^2) in the 1999/2000 growing season.

Crop dry matter			Weed dry matter		
Crop density	Sowing 1	Sowing 2	Crop density	Sowing 1	Sowing 2
	Lupin	Bean		Lupin	Bean
0.5	1,214.0	348.0	0.5	125.0	397
1.0	1,154.0	503.0	1.0	106.0	51
2.0	1,130.0	548.0	2.0	59.0	34
4.0	1,122.0	416.0	4.0	7.0	12
	Rape	Turnip		Rape	Turnip
0.5	792.0	86.0	0.5	189.0	0.2
1.0	612.0	120.0	1.0	99.0	0.7
2.0	926.0	126.0	2.0	71.0	0.0
4.0	788.0	193.0	4.0	26.0	1.4
	Ryecorn	Maize		Ryecorn	Maize
0.5	550.0	2,065.0	0.5	51.0	106.0
1.0	569.0	2,809.0	1.0	26.0	20.4
2.0	548.0	1,652.0	2.0	15.0	0.0
4.0	635.0	1,598.0	4.0	18.0	0.0
Significance					
Crop	***			***	
Density	NS			***	
SEM	138.9			28.9	
CV (%)	28.2			86.1	

NS, non-significant; *, P < 0.05; **, P < 0.01; ***, P < 0.001; ND, not determined. Crop density – 0.5, 1.0, 2.0, and 4.0 x optimum population.

±

Table 3.4: Orthogonal contrasts of weed dry matter (g/m^2) under crop treatments at 60 DAS and final harvests in the 1999/2000 growing season.

Contrasts	60 DAS	Final harvest
Sowing		
1	256.4	792.0
2	161.5	622.7
Significance	ns	Ns
Legumes		
Lupin	62.9	297.0
Bean	94.1	494.0
Significance	ns	*
Brassicas		
Rape	160.0	385.0
Turnip	20.7	2.3
Significance	**	***
Cereals		
Ryecorn	33.1	110.0
Maize	46.8	126.4
Significance	ns	Ns

NS, non-significant, *, $p < 0.05$, **, $p < 0.01$, ***, $p < 0.001$.

3.3.4 Seed Yield

The maximum mean grain yield of 9.3 t/ha was produced by the maize followed by lupin, bean and ryecorn at 4.2, 2.3 and 1.2 t/ha respectively. There were significant differences in grain yield among the different densities ($p < 0.001$). Plant population in maize significantly affected grain yield ($p < 0.05$). There was a marked decline in yield with increased density from 13.3 – 5.2 t/ha (0.5 – 4.0 x optimum population). Ryecorn grain yield was relatively constant across densities. Lupin showed a steady seed yield decline from 5.4 – 3.2 t/ha (0.5 – 4.0 x optimum population). However, bean yield increased from the 0.5 x optimum population to the 2.0 x optimum population (1.8 – 2.9 t/ha) and then declined at 4.0 x optimum population (2.0 t/ha). The lowest and highest grain yields were recorded at highest and lowest plant populations respectively (Figure 3.6: 3.7).

Maximum grain yield was obtained at 0.5 x optimum population for lupin, ryecorn, and maize, although these crops were in direct interplant competition with the weeds. Grain yield/plant was therefore strongly influenced by plant population. Appendix 3 shows some components of grain yield for two crops (cobs/m^2 – maize and pods/m^2 for beans). The highest number of cobs/m^2 and pods/m^2 were obtained at 0.5 x optimum population and decreased from 2 – 1 cob/m^2 for maize and from 16.7 – 4.7 pods/m^2 for bean (0.5 – 4.0 x optimum population).

Grain yield was related positively and linearly with weed DM in lupin and maize (r^2 = 0.47 and r^2 = 0.51 respectively) (Figure 3.10). Additionally, the relationship between seed yield and crop DM was also positive in these two crops (Figure 3.9). With increased weed and crop DM seed yield was highest at the 0.5 x optimum population for lupin and 1.0 x optimum population for maize.

3.3.5 Harvest Index

Bean had the highest HI of all of the grain crops (0.48) followed by maize (0.39), lupin (0.36) and ryecorn (0.19). The HI generally decreased with increased plant density (Figure 3.6, 3.7). The 0.5 x optimum population had the highest HI for all crops that bore seed. Harvest indices ranges from 0.54 – 0.42, 0.50 – 0.23, 0.44 – 0.29, and 0.21 – 0.29 in bean, maize, lupin and ryecorn respectively at the 0.5 – 4.0 x optimum populations and were significantly different ($p < 0.001$).

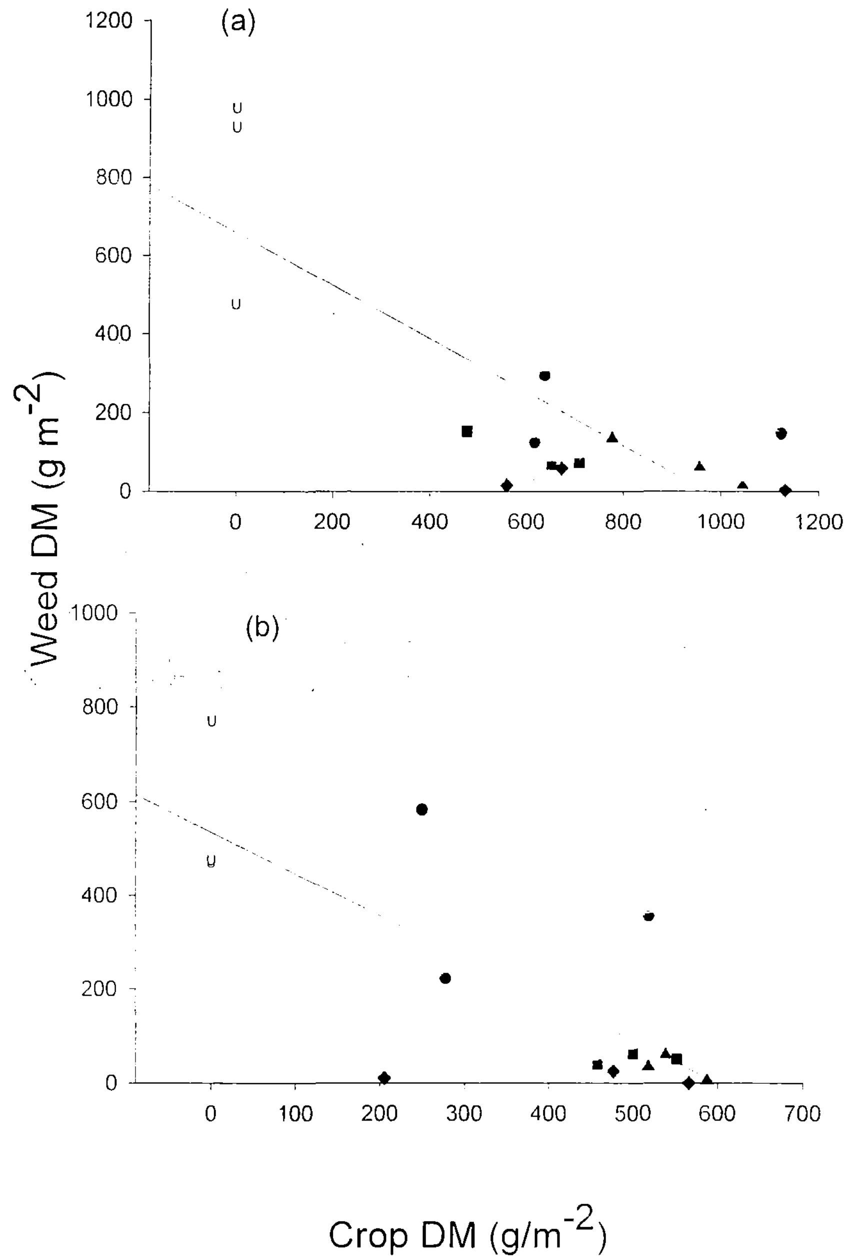

Figure 3.4. The relationship between crop yield and total weed dry matter present at final harvest for rape and bean. (U) = No crop control, 0.5 (●), 1.0 (∇), 2.0 (■), and 4.0 (◊) x optimum population ** and *** correlation significant at $p < 0.01$ and 0.001 levels respectively.
(a) Rape – $Y = 658.7 - 0.68\ x$, ($r^2 = -0.82^{***}$).
(b) Bean – $Y = 534.8 - 0.89\ x$, ($r^2 = -0.78^{**}$)

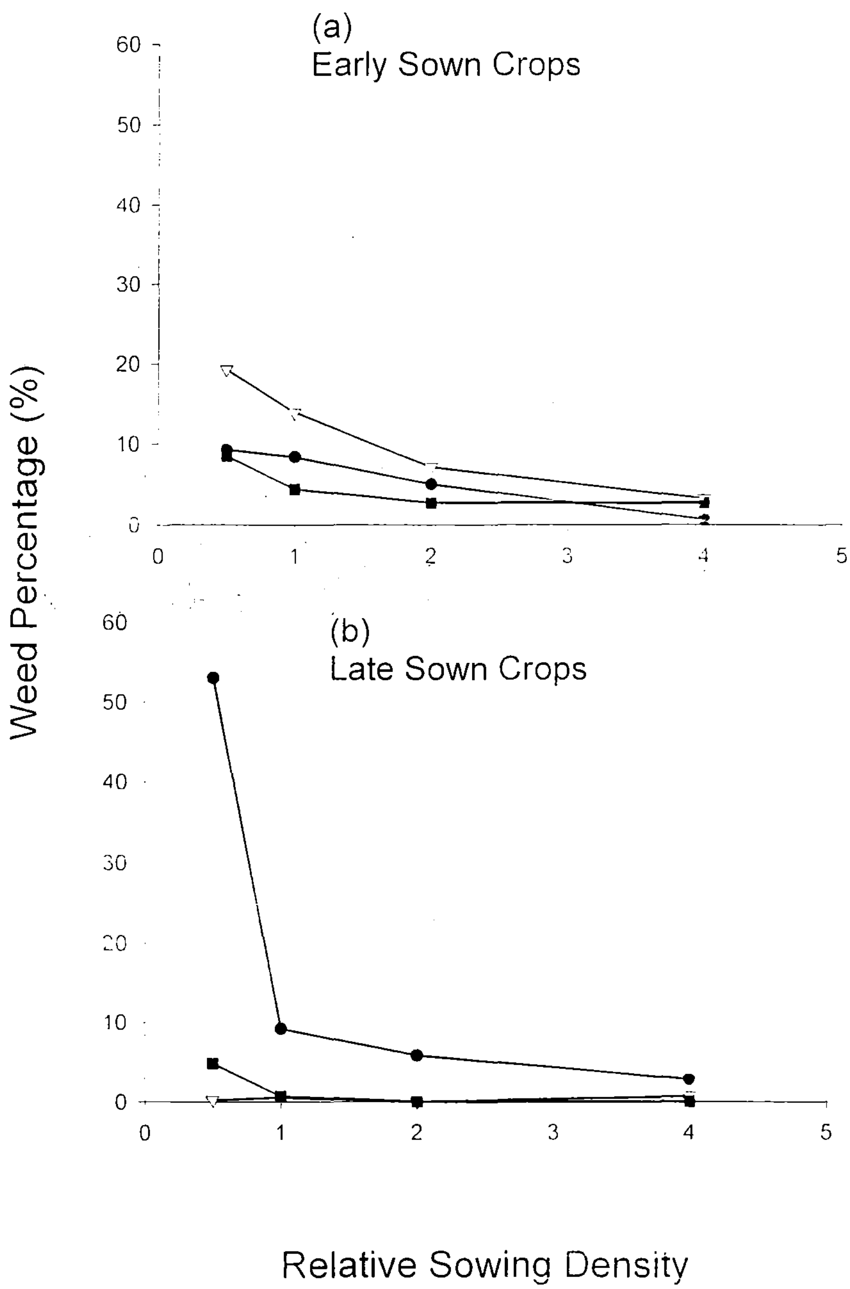

Figure 3.5. Weed dry matter as a percentage of TDM at relative sowing density (0.5, 1.0, 2.0 and 4.0 x optimum plant population) for the early (lupin (●), rape (▽), ryecorn (■)) late sown crops (bean (●), turnip (▽), maize (■)) at final harvest.

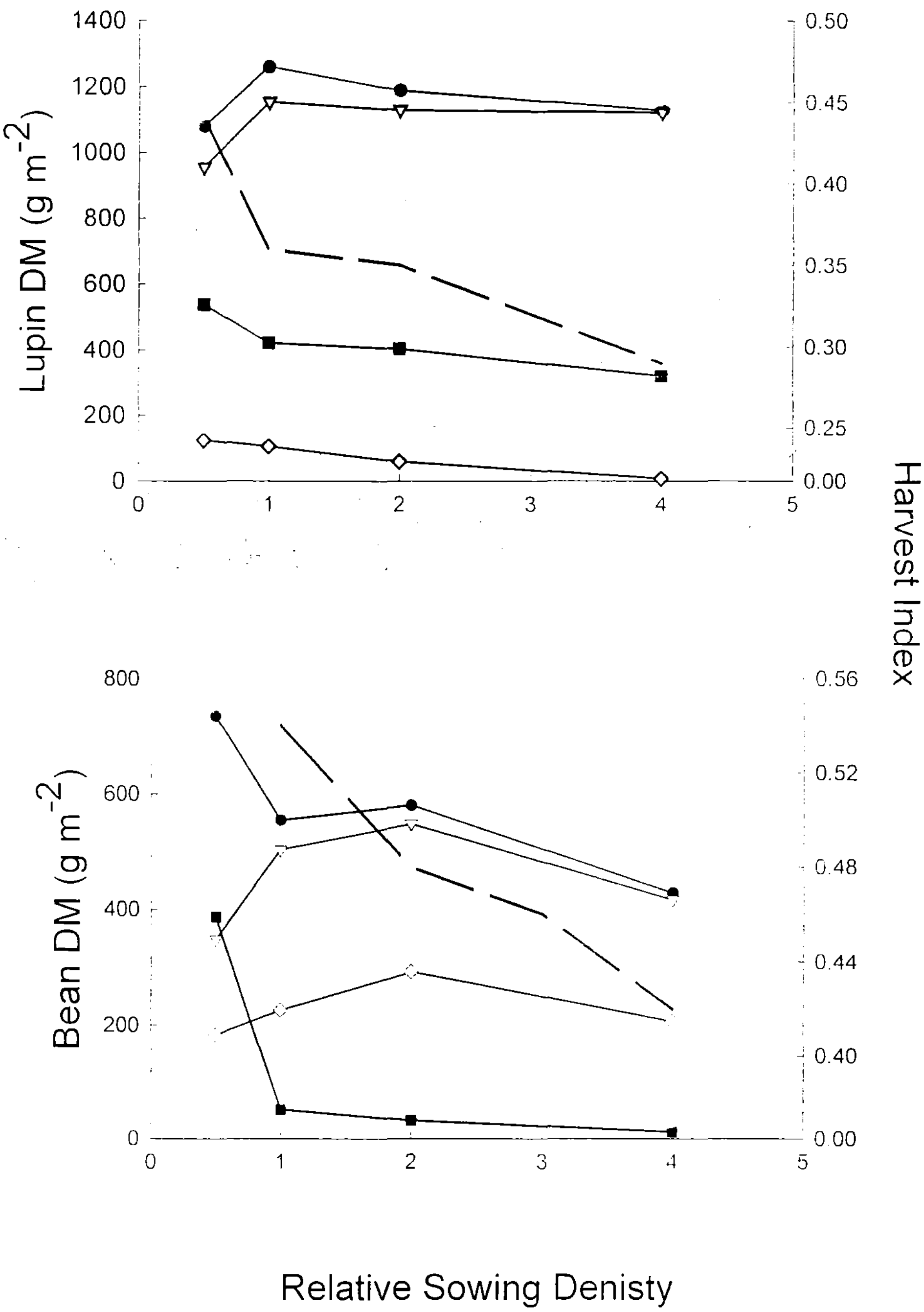

Figure 3.6. Total crop and weed productivity and crop harvest index as affected by relative sowing density (●) – Total crop and weed (TDM), (▽) – crop DM, (■) – weed DM,(◊) – seed yield, (---) and harvest index for lupin and bean.

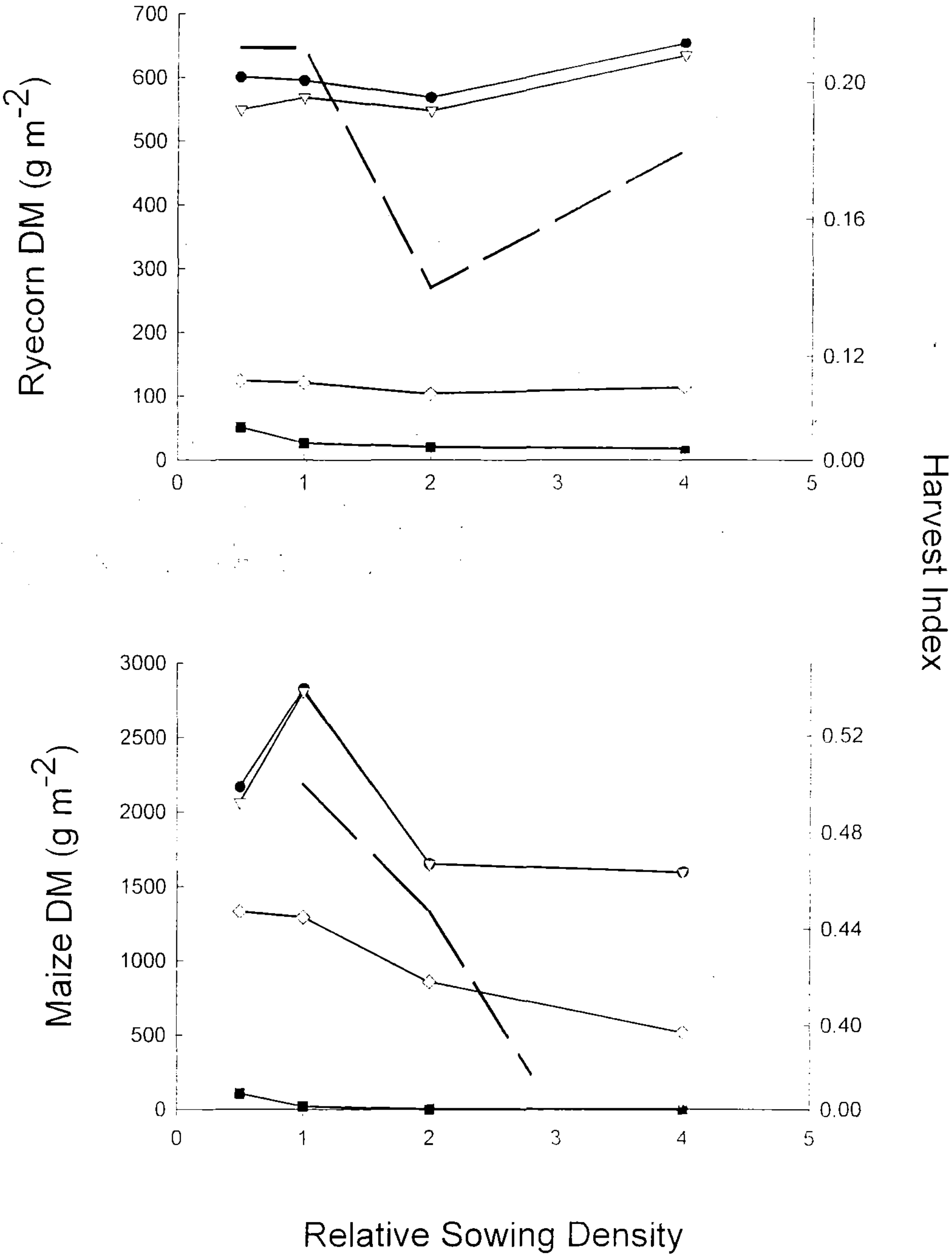

Figure 3.7. Total crop and weed productivity and crop harvest index as affected by relative sowing density (●) – Total crop and weed (TDM), (▽) – crop DM, (■) – weed DM,(◊) – seed yield, (---) and harvest index for ryecorn and maize.

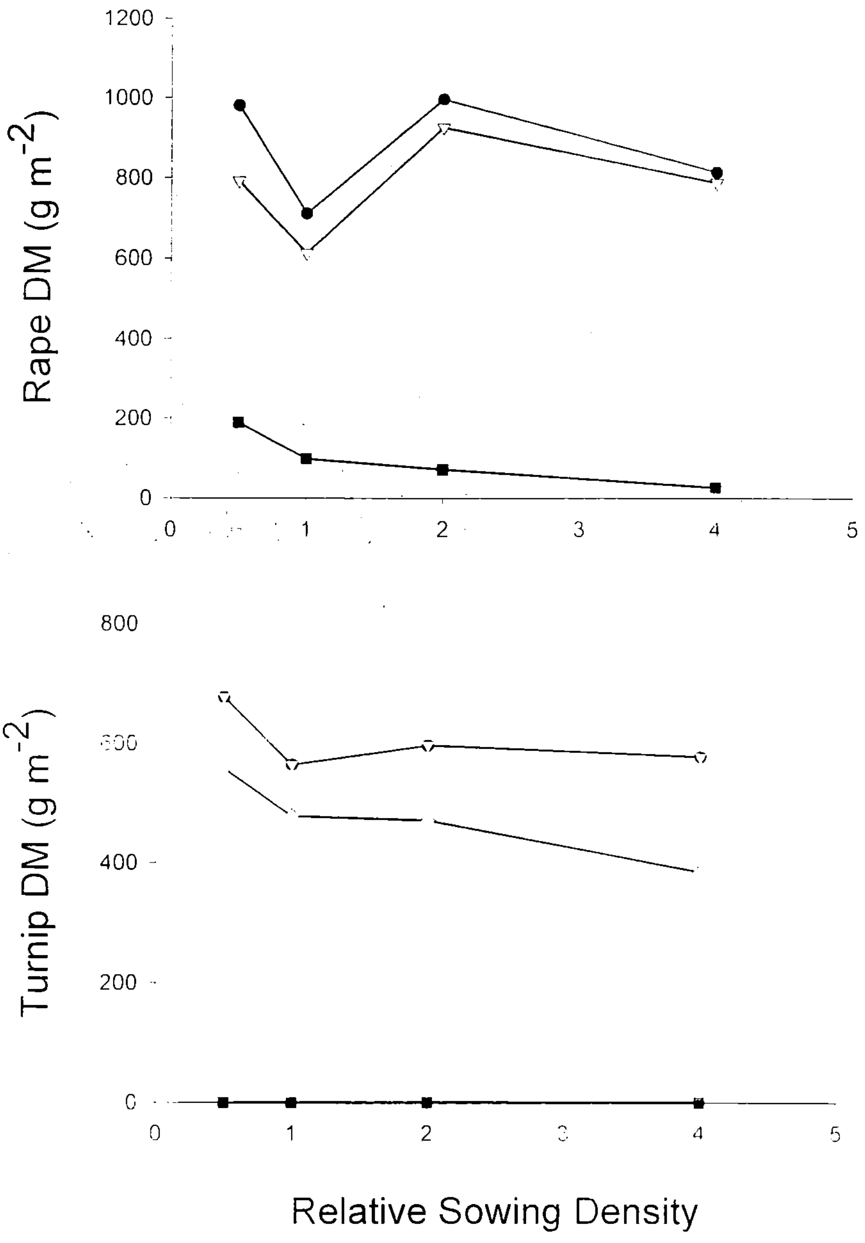

Figure 3.8. Total crop and weed productivity as affected by relative sowing density (●) – Total crop and weed (TDM). (▽) – crop DM. (■) – weed DM.(◊) for rape and turnip.

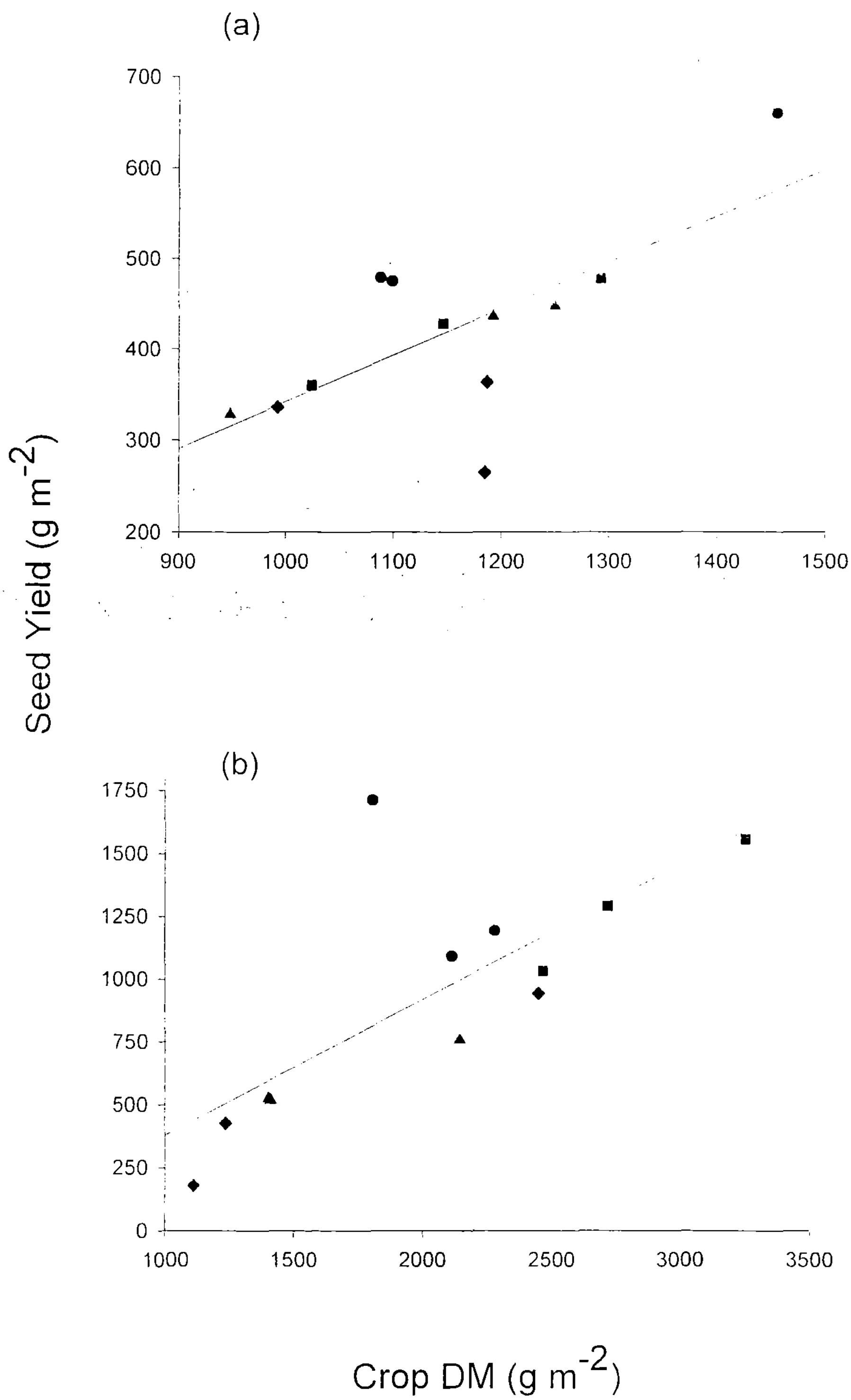

Figure 3.9. Relationship between seed yield and crop DM for (a) lupin and (b) maize. 0.5 (●), 1.0 (■), 2.0 (▲), 4.0 (◆) x optimum population.
(a) Lupin – Y = -172 + 0.51 x (r^2 = 0.49**)
(b) Maize – Y = -163 + 0.54 x (r^2 = 0.57**)

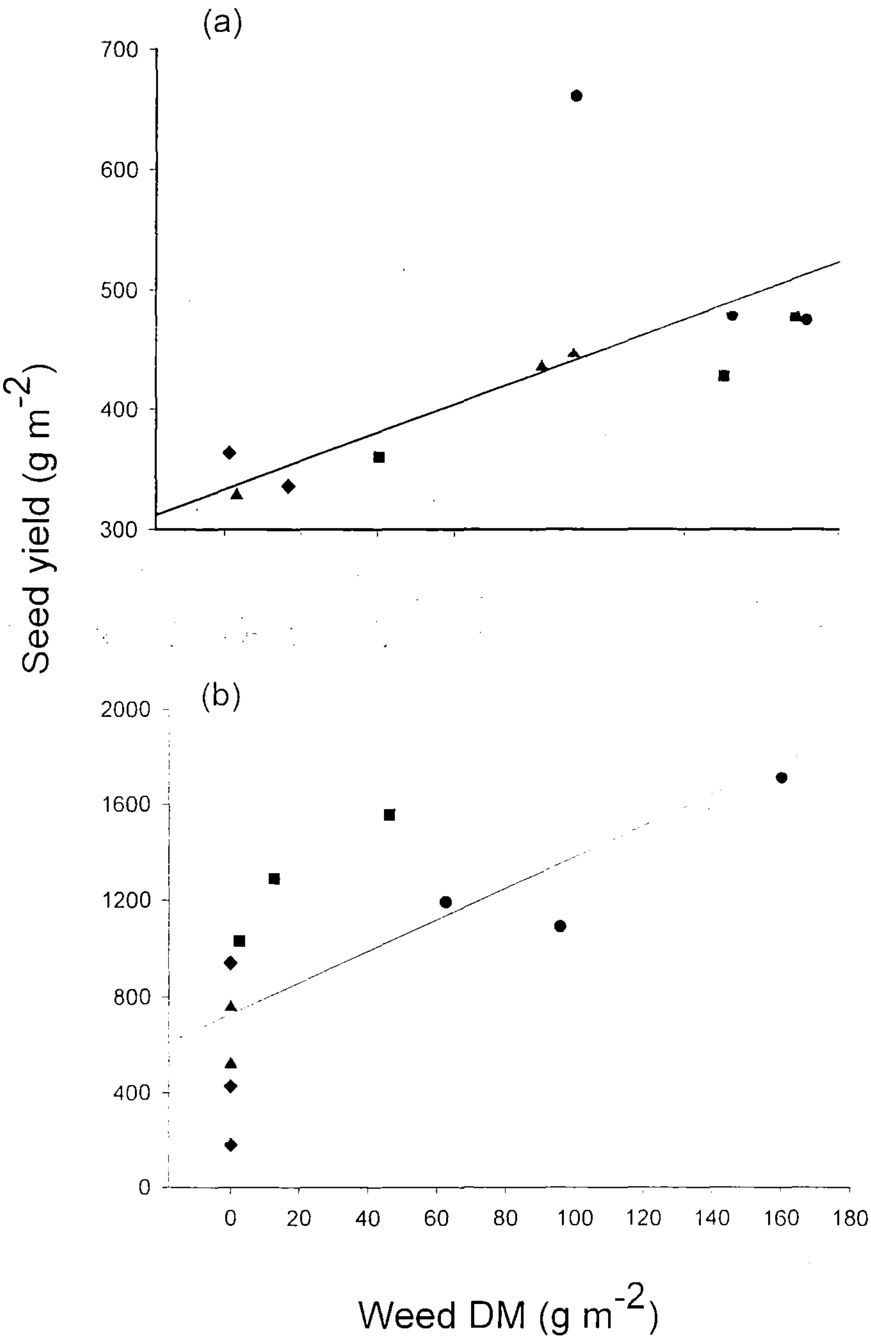

Figure 3.10. Relationship between seed yield and weed DM for (a) lupin and (b) maize. 0.5 (●), 1.0 (■), 2.0 (▲), 4.0 (◆) x optimum population.
(a) Lupin – Y = 333 + 1.2 x (r^2 = 0.47*)
(b) Maize – Y = 729 + 6.5x (r^2 = 0.51**)

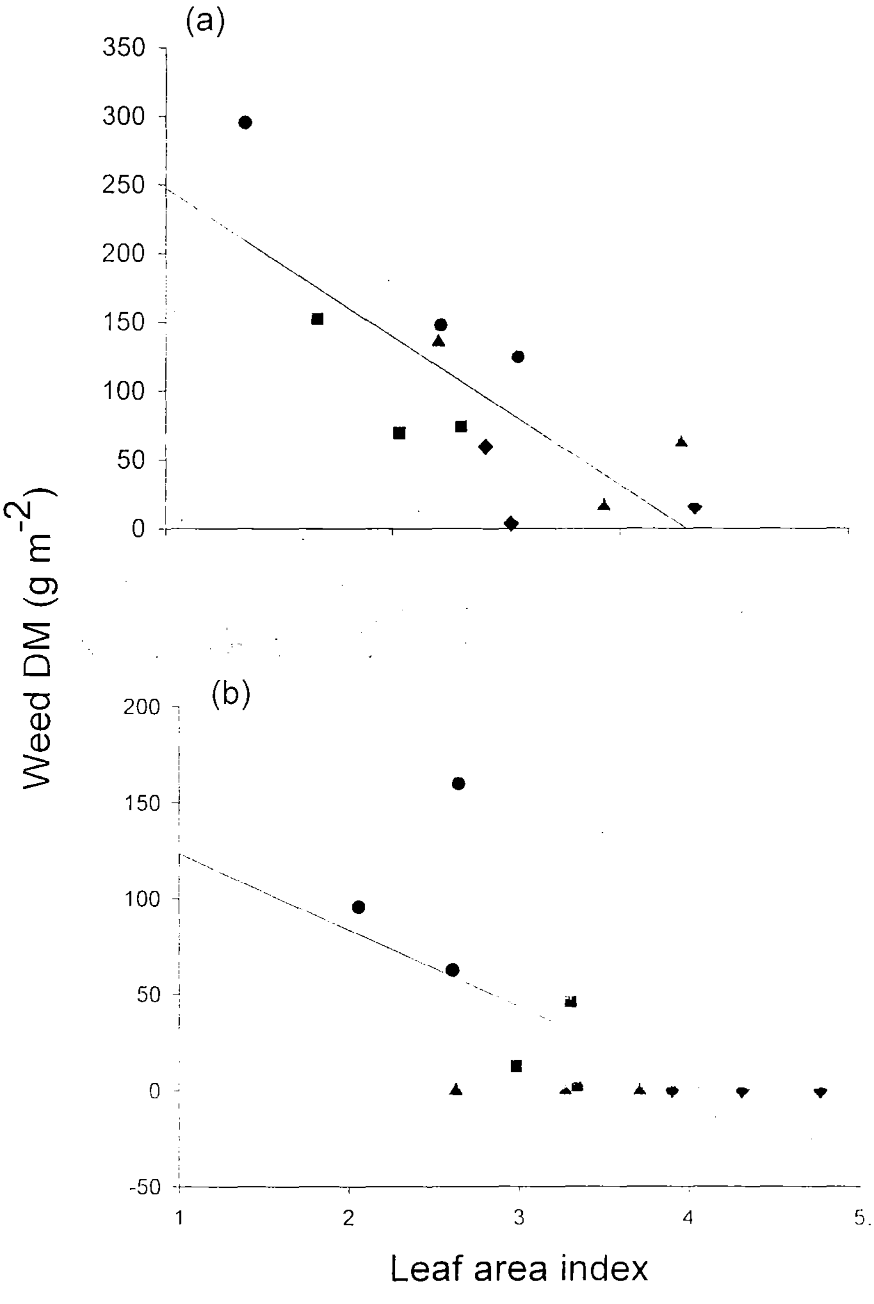

Figure 3.11. The relationship between weed biomass and LAI for rape and maize. 0.5 (●), 1.0 (■), 2.0, (▲), 4.0 (◆) x optimum population.
(a) Rape – Y = 463.5 – 107.8 x (r^2 = - 0.78**)
(b) Maize – Y = 163.5 + 40.0 x (r^2 = - 0.61*)

3.3.6 Leaf area index, radiation interception and radiation use efficiency

Leaf area index: Averaged overall populations achieved a maximum leaf area index (LAI) of 4.1 in turnip at 60 DAS while other crops such as bean and maize had attained LAI's of only 0.66 and 1.1 respectively by the same time ($p < 0.001$).

Leaf area index increased with increased plant population (Figure 3.12). At 60 DAS turnip, which produced the highest, LAI increased its LAI from 3.5 – 5.1 from 0.5 to 4.0 x optimum population. Lupin increased from 1.9 – 3.7, rape from1.5 – 3.5, ryecorn from 1.3 – 3.8 and maize from 0.4 – 2.0. This trend of increased LAI with increased plant population varied later (105 – 150 DAS).

Figure 3.12 shows the changes in LAI over time for the 6 crops at the different crop densities. Leaf area index, which increased with time, peaked at 105 DAS (6.1) for turnip at 1.0 x optimum population. However, maize, bean, lupin, ryecorn and rape peaked at 135, 120, 105, 105 and 90 DAS at 5.3, 5.4, 5.2, 4.3 and 4.8 at 4.0 x optimum population respectively. At 0.5 x optimum population the LAI peaked at 90 DAS for turnip (5.7) and rape (3.1), 105 DAS for ryecorn (3.6), 120 DAS for lupin (3.3) and 150 DAS for bean (3.1) and maize (2.4).

Radiation interception: Leaf area index strongly influenced radiation interception (Figures 3.13; 3.14). A LAI of 3.0 was required to intercept at least 95 % of the incident solar radiation (defined as canopy closure) for maize, 3.5 for lupin, rape, bean, turnip and ryecorn. At 4.0 x optimum population, canopy closure was achieved at 50 DAS for turnip, 60 DAS for lupins, ryecorn, and rape, 83 DAS for maize and 85 DAS for bean. At 0.5 x optimum population lupin, rape, ryecorn, bean and maize never achieved canopy closure while turnip attained it at 60 DAS. In rape, and ryecorn canopy closure was also never achieved at 1.0 x optimum population. It was achieved at 60, 105 and 120 DAS in turnip, bean and maize respectively.

Light measurements showed that as density of each crop increased from 0.5 to 4.0 x optimum plant population, the available light reaching the bottom of the canopy decreased. Transmittance through the canopy declined with time with a decrease with increased plant population from 0.5 – 4.0 x optimum population according to the non-linear sigmoid regression model which was fitted to the transmittance and DAS data (Equation 3.2) (Table 3.5). Figure 3.17 and 3.18 shows the fraction of light transmitted through the canopy to the soil as a function of the DAS for the different crops at increasing plant population.

There was a marked difference among the different crop treatments in canopy closure. However, there was little difference in the rate of closure among the density treatments for each crop. Crops at the highest population (4.0 x optimum population) closed 24.0, 33.9, 41.0, 21.4, 18.3, and 31.3 days earlier than the lowest population (0.5 x optimum population) for lupin, rape, ryecorn, bean, turnip and maize respectively. Overall, turnip at all plant populations closed its canopy earlier than beans, followed by maize, ryecorn, rape and finally lupin (Figure 3.17 and 3.18).

There was a significant crop effect on total accumulated PAR for the early and late sown crops ($p < 0.001$). Turnip intercepted the most solar radiation at 1068.1 MJ/m^2 which was 354.2 MJ/m^2 more than bean which intercepted the least PAR. Total intercepted PAR increased with increased plant population from 0.5 – 4.0 x optimum population for all crops: turnip (1027.3 – 1117.9 MJ/m^2), lupin (766.6 – 886.0 MJ/m^2), maize (611.3 – 955.5 MJ/m^2), rape (678.6 – 868.6 MJ/m^2), ryecorn (657.7 – 860.0 MJ/m^2) and bean (586.7 – 823.2 MJ/m^2). There was a significant crop x density interaction between the different crops ($p < 0.001$) (Table 3.6).

Radiation interception and dry matter accumulation: For all treatments there was a strong linear relationship between cumulative intercepted PAR and cumulative DM yield in all crops (Figure 3.15; 3.16). Correlations of 0.77, 0.76, 0.87, 0.68, 0.71 and 0.67 were calculated for lupin, rape, ryecorn, bean, turnip and maize respectively. Averaged overall populations in maize produced more DM per MJ of intercepted PAR than all the other crops at 3.4 g DM for every MJ intercepted PAR. This was followed by lupin, ryecorn, rape, bean and turnip at 1.7, 1.2, 0.98, 0.96 and 0.37 g DM for every MJ PAR intercepted, respectively (Table 3.6).

The radiation use efficiency (RUE) values, based on cumulative intercepted PAR from emergence to physiological maturity for individual treatments, are shown in Table 3.6. Maize had the highest RUE's ranging from 5.5 – 2.7 g DM/MJ PAR, followed by lupin 1.9 – 1.5 g DM/MJ PAR and turnip, the lowest ranged from 0.2 to 0.4 g DM/MJ PAR (0.5 – 4.0 x optimum populations). There were no observed trends in RUE with increased plant population. However, the highest RUE was at 0.5 x optimum population for maize, lupin and rape (5.5, 1.9, and 1.2 respectively), 1.0 x optimum population for ryecorn and turnip (1.6 and 0.5 respectively), and 2.0 x optimum population for bean (1.2). The lowest RUE's were observed at the 4.0 x optimum population for maize, lupin, ryecorn, bean and rape (2.7, 1.5, 1.0, 1.0 and 0.6 respectively).

Table 3.5. Regression model of fraction of light transmitted through the canopy as a function of days after sowing for 6 crops.

Crop treatment[a]	B	C	Model (r^2)
Lupin			
0.5	2.29	37.9	0.98
1.0	2.73	36.6	0.99
2.0	2.97	32.5	0.97
4.0	1.85	13.9	0.79
Rape			
0.5	3.62	53.8	0.92
1.0	2.34	39.7	0.75
2.0	2.57	32.5	0.94
4.0	2.04	19.9	0.79
Ryecorn			
0.5	3.85	56.2	0.98
1.0	2.84	45.9	0.91
2.0	2.58	35.6	0.85
4.0	1.81	15.2	0.64
Bean			
0.5	3.97	79.9	0.96
1.0	5.63	68.6	0.94
2.0	5.95	65.8	0.79
4.0	6.22	58.5	0.93
Turnip			
0.5	3.40	30.9	0.83
1.0	3.73	33.9	0.87
2.0	2.60	18.1	0.82
4.0	2.00	12.6	0.26
Maize			
0.5	3.22	73.5	0.96
1.0	3.41	60.7	0.89
2.0	3.98	51.8	0.96
4.0	3.98	42.2	0.96

[a]Crop treatment for each crop – 0.5, 1.0, 2.0 & 4.0 x optimum population.

[b]and [c] Coefficients from the model $Y = 1/(1+(X/c)^b)$ where Y = light transmitted and X = DAS

Table 3.6. Total intercepted radiation and radiation use efficiency (RUE) of 6 crop species at four plant populations in the 1999/2000 growing season.

Crop treatment	PAR (MJ/m^2)	RUE (g DM/MJ PAR)
Lupin		
0.5	767.0	1.93
1.0	797.1	1.70
2.0	833.0	1.90
4.0	886.0	1.45
Rape		
0.5	679.0	1.22
1.0	762.3	1.00
2.0	827.4	1.12
4.0	869.0	0.61
Ryecorn		
0.5	658.0	1.27
1.0	721.1	1.60
2.0	784.4	1.26
4.0	860.0	1.04
Beans		
0.5	587.0	1.04
1.0	682.0	0.84
2.0	764.0	1.24
4.0	823.2	0.72
Turnip		
0.5	1027.3	0.20
1.0	1033.0	0.48
2.0	1094.2	0.42
4.0	1118.0	0.38
Maize		
0.5	611.3	5.54
1.0	741.0	5.09
2.0	841.1	3.83
4.0	956.0	2.66
Significant interactions	***	*

Crop treatment for each crop – 0.5, 1.0, 2.0 & 4.0 x optimum population. ns – non- significant, * $p < 0.05$, ** $p < 0.01$.

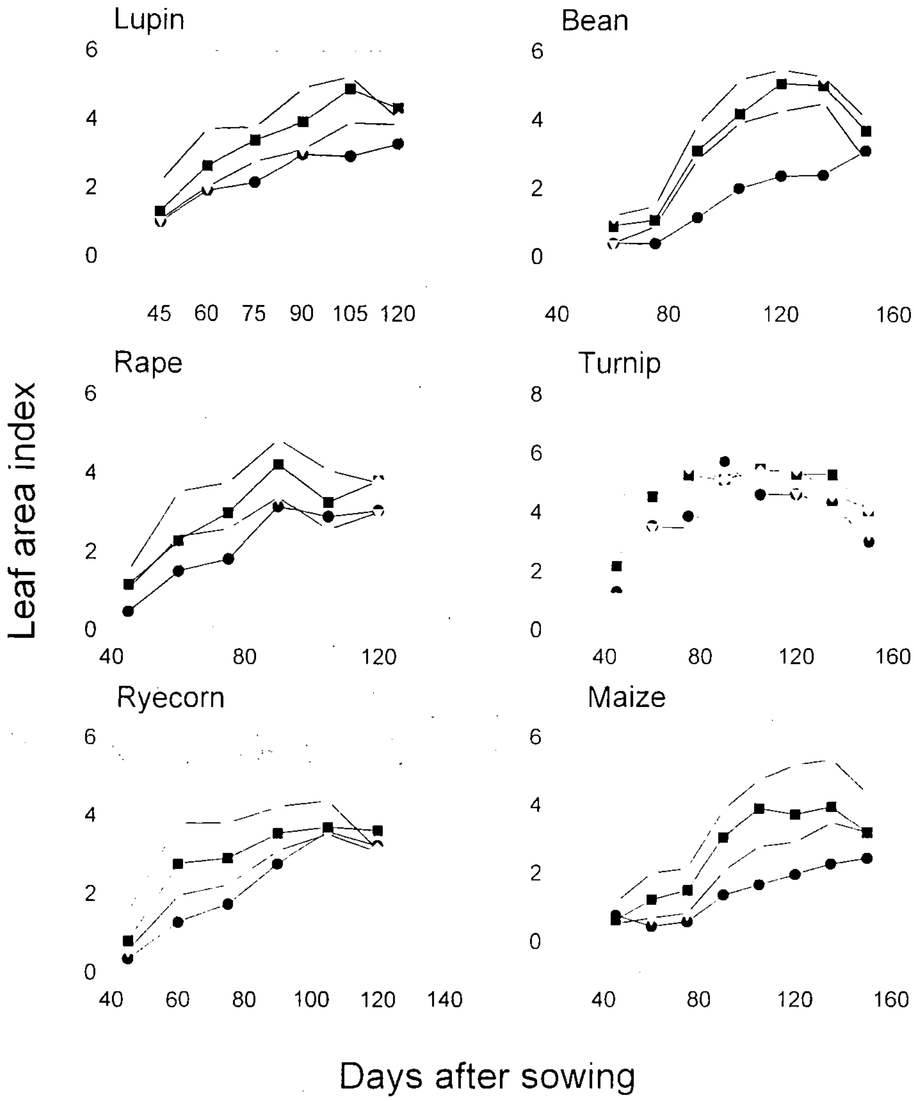

Figure 3.12. The changes in LAI for 6 crops at 0.5 (●), 1.0 (▽), 2.0 (■), 4.0 (◊) x optimum population over the growing season 1999/2000. Bars indicate SEM.

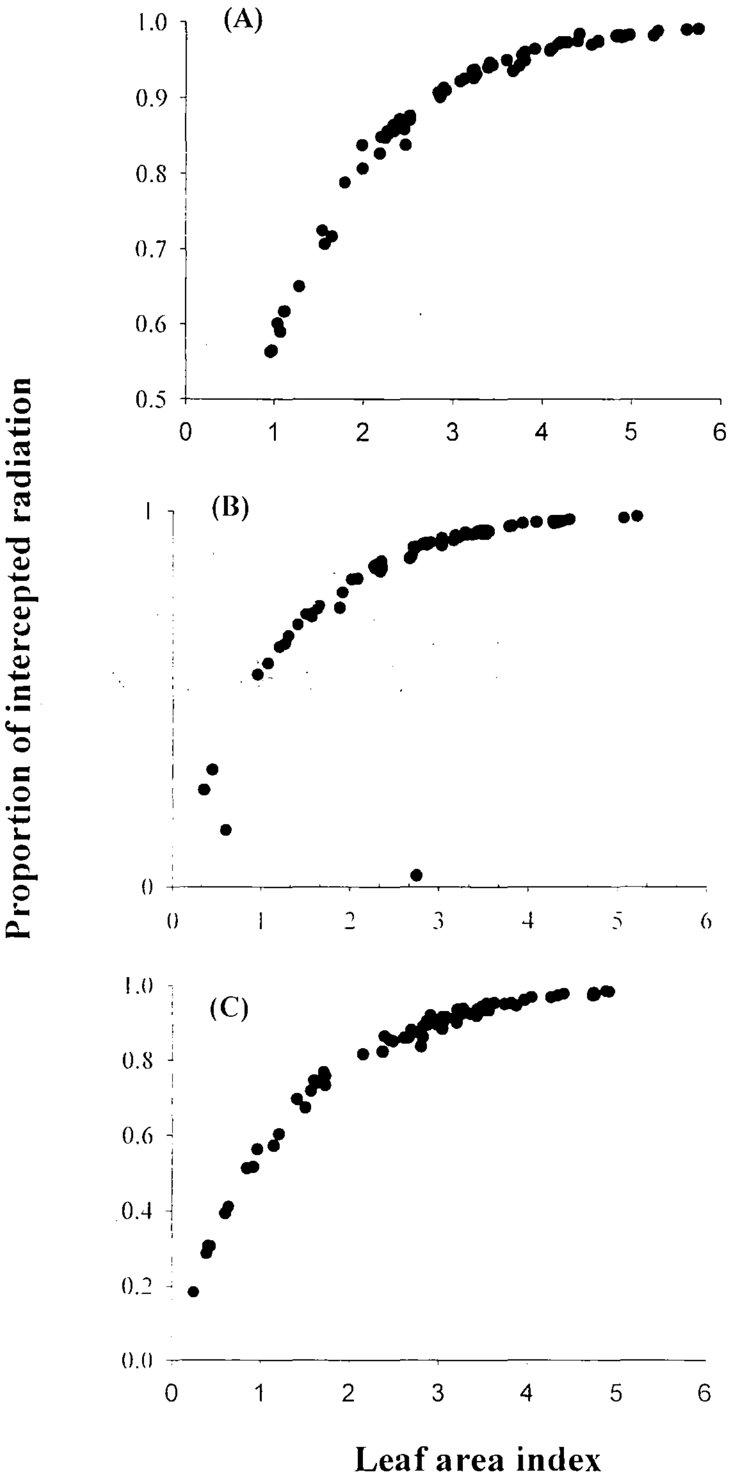

Figure 3.13. Relationship between leaf area index and the proportion of intercepted radiation for the early sown crops in the 1999/2000 growing season.
(a) Lupin – $Y = 1 - e^{-0.79 LAI}$
(b) Rape – $Y = 1 - e^{-0.43 LAI}$
(c) Ryecorn – $Y = - e^{-0.46 LAI}$

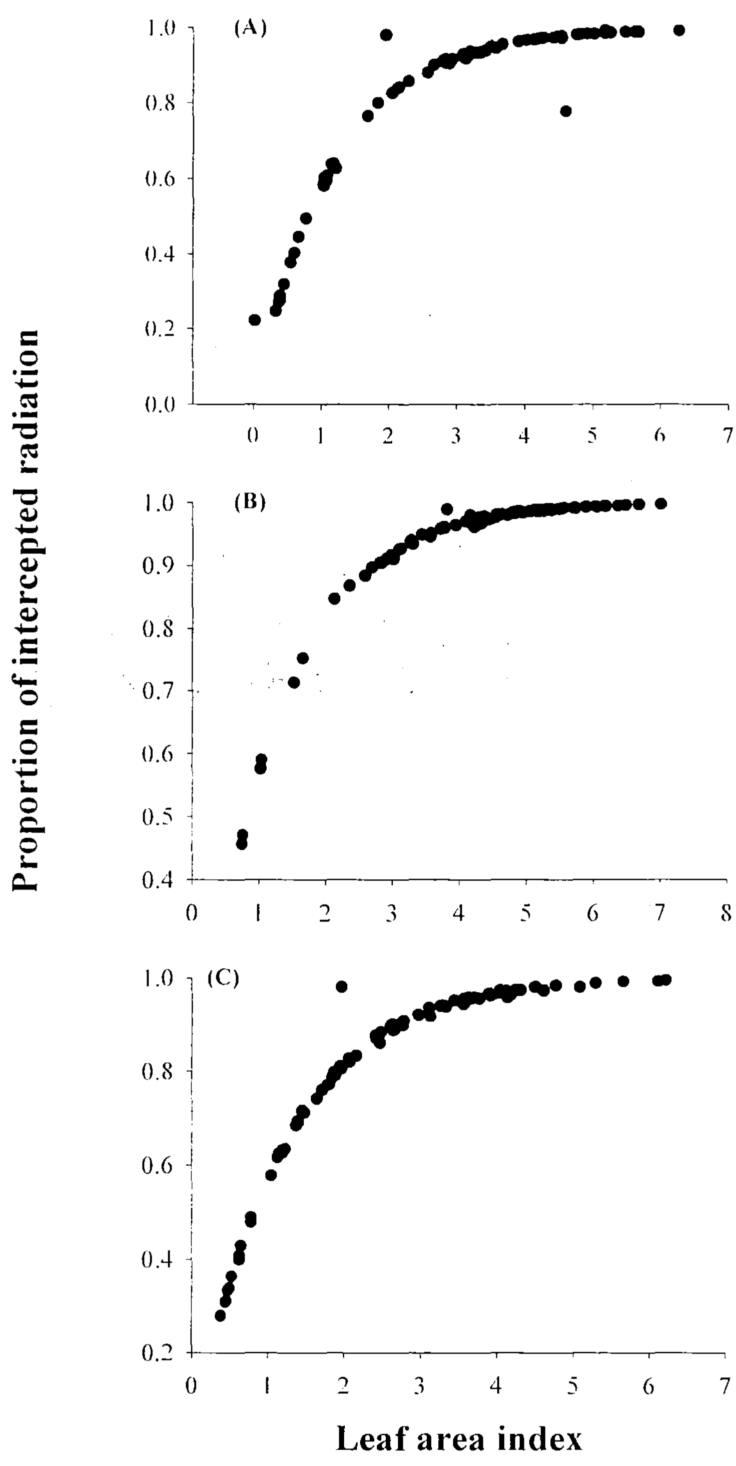

Figure 3.14. Relationship between leaf area index and the proportion of intercepted radiation of the late sown crops in the 1999/2000 growing season.

(a) Bean – $Y = 1 - e^{-0.31 \, LAI}$

(b) Turnip – $Y = 1 - e^{-0.85 \, LAI}$

(c) Maize – $Y = - e^{-0.78 \, LAI}$

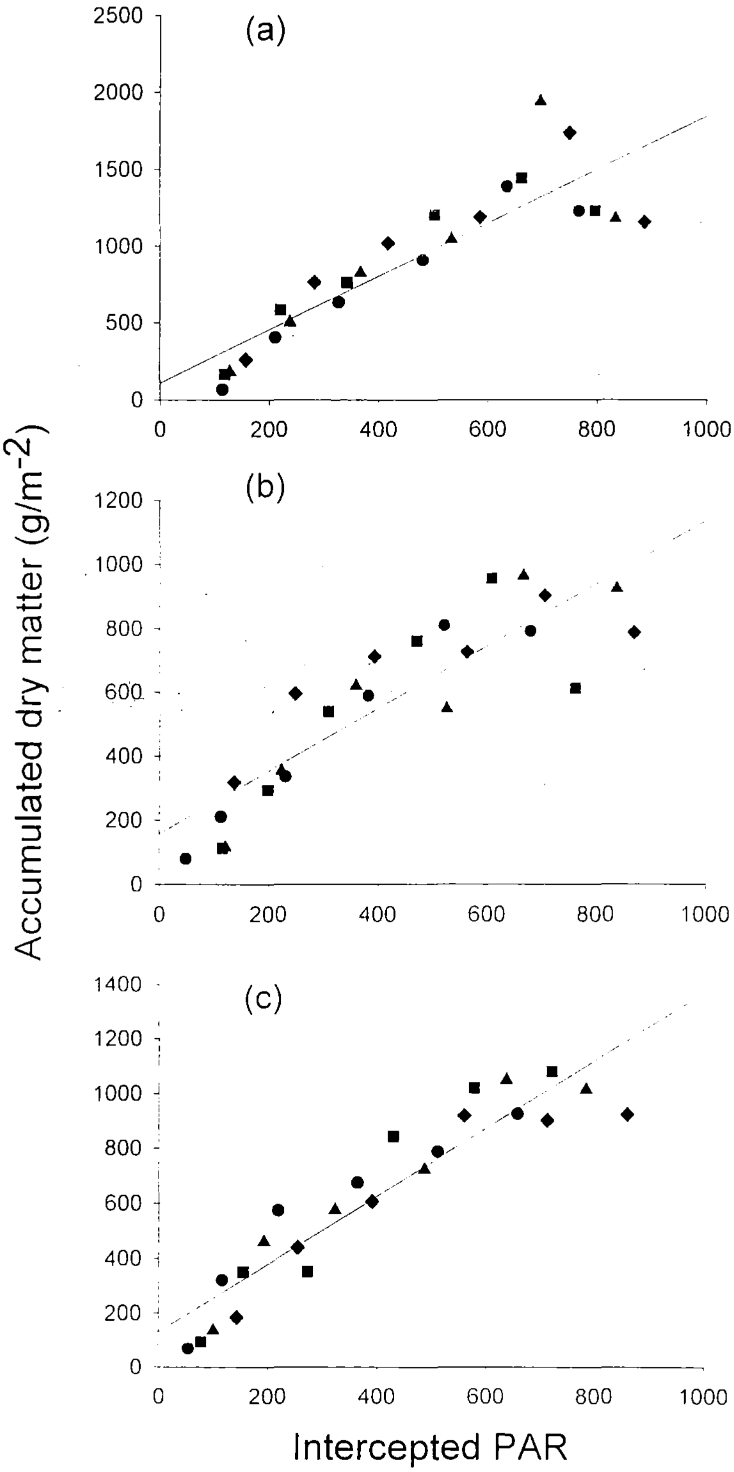

Figure 3.15. The relationship between accumulated DM and intercepted PAR for lupin, rape and ryecorn at 0.5 (●), 1.0 (■), 2.0 (▲) and 4.0 (♦) x optimum populations.
(a) Lupin – Y = 107.0 + 1.74 x (r^2 = 0.77***).
(b) Rape – Y = 158.0 + 0.98 x (r^2 = 0.76***).
(c) Ryecorn – Y = 131.0 + 1.2 x (r^2 = 0.87***).

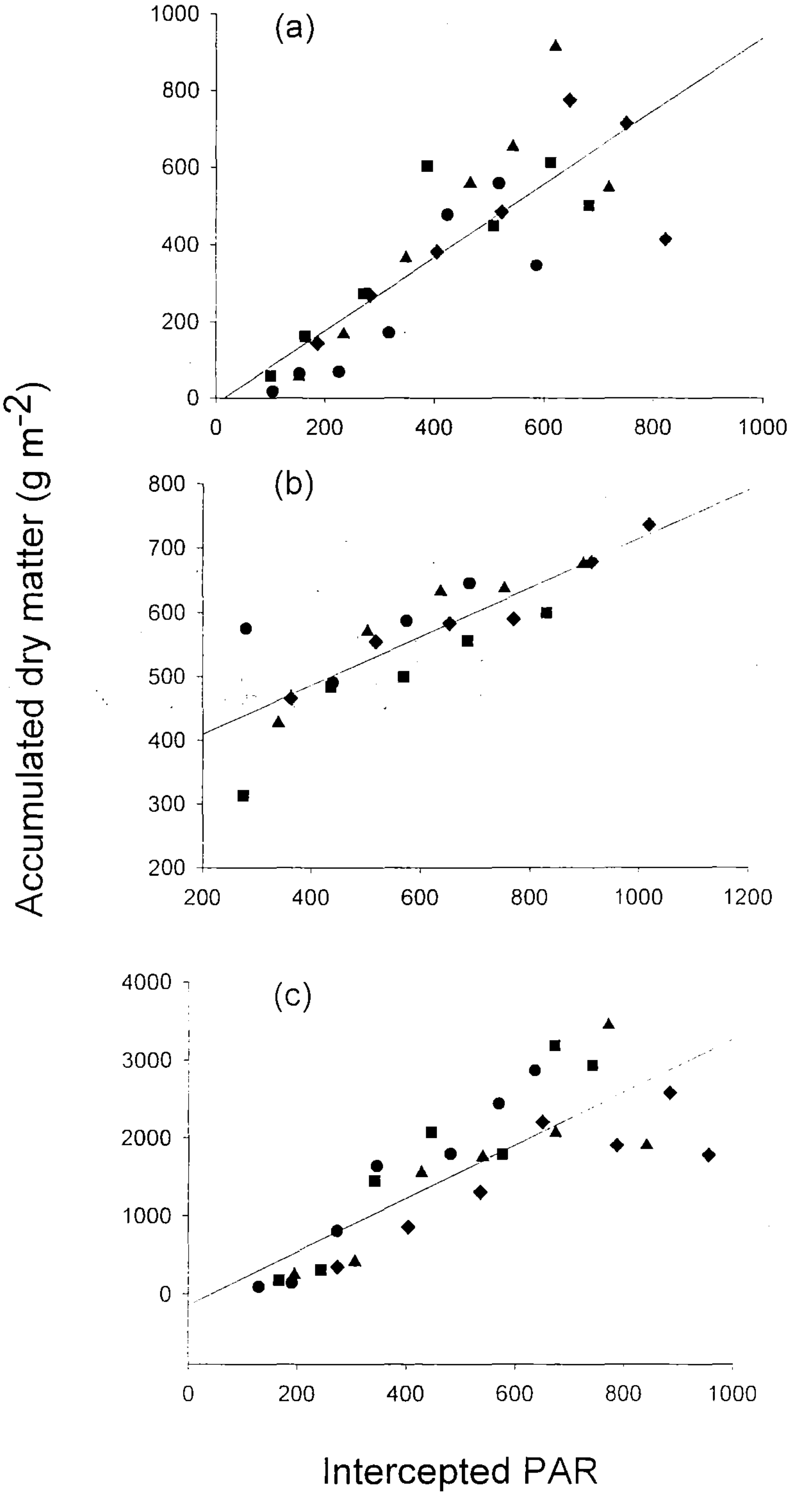

Figure 3.16. The relationship between accumulated DM and intercepted PAR for bean, turnip, and maize at 0.5 (●), 1.0 (■), 2.0, (▲), 4.0 (◆) x optimum population.

(a) Bean – Y = -13.7 + 0.95 x (r^2 = 0.68***)

(b) Turnip – Y = 334.0 + 0.38 x (r^2 = 0.71***)

(c) Maize – Y = -143.0 +3.4 x (r^2 = 0.67***)

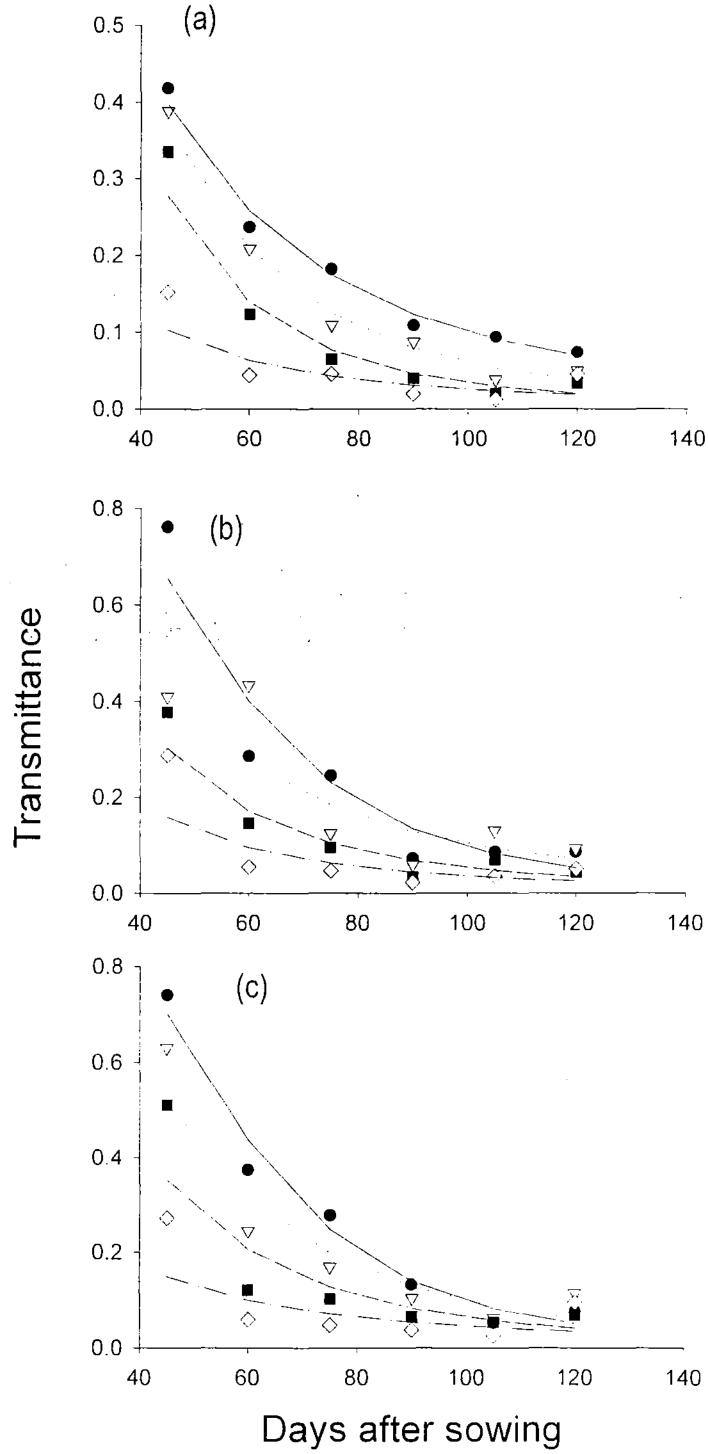

Figure 3.17. The fraction of light transmitted through the canopy to the soil surface as a function of days after sowing (DAS) for the early sown crops. 0.5 (●), 1.0 (▽), 2.0 (■), 4.0 (◊) x optimum population over the growing season 1999/2000. (a) lupin, (b) rape and (c) ryecorn.

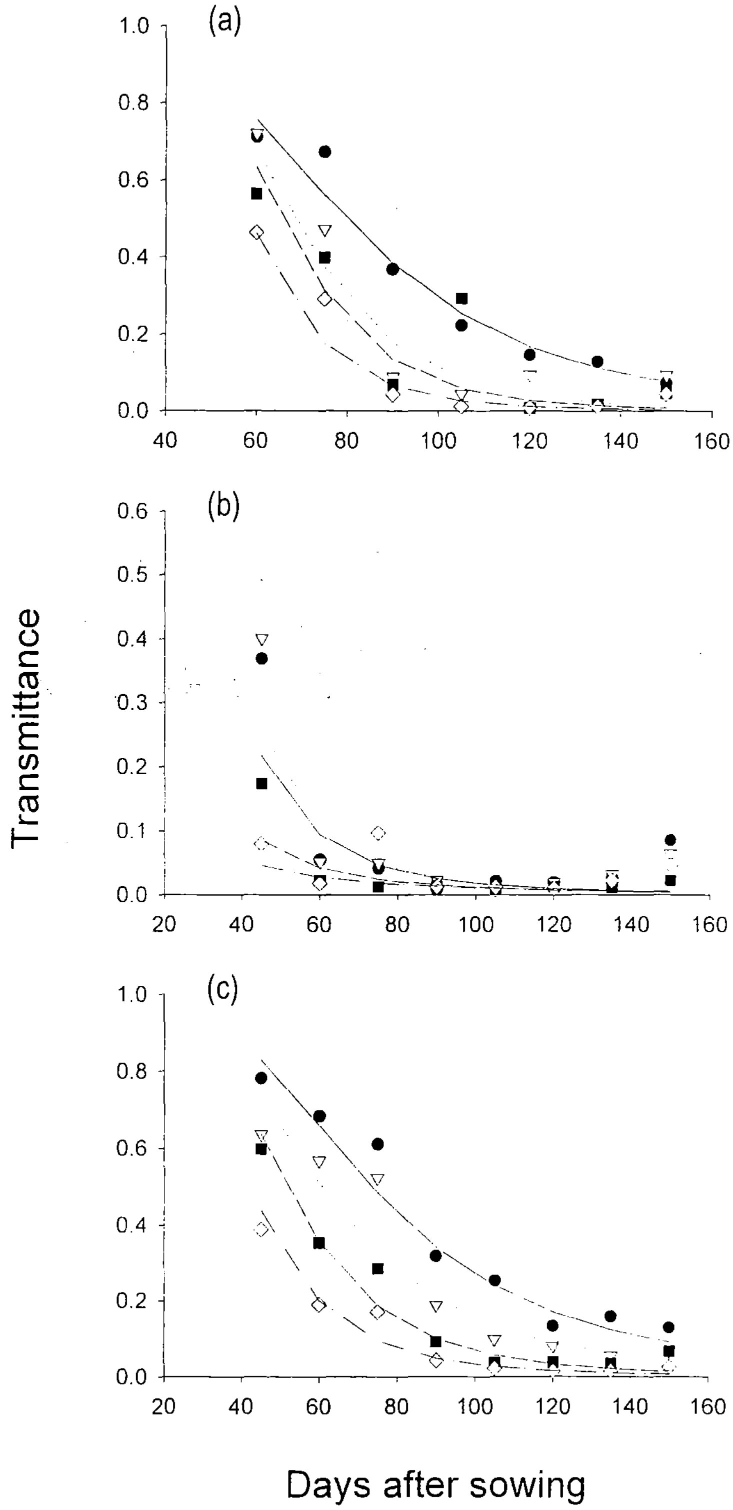

Figure 3.18. The fraction of light transmitted through the canopy to the soil as a function of days after sowing (DAS) for the late sown crops. 0.5, (●), 1.0 (▽), 2.0 (■), 4.0 (◊) x optimum recommended sowing rate over the growing season 1999/2000. (a) bean, (b) turnip and (c) maize

3.4 Discussion

The effect of crop species and density on crop and weed productivity: The climate throughout the growing season was favourable for all crops resulting in high DM production. Initial growth of the maize and bean were greatly affected by saturated cool soils during early November and December (Figure 3.1). Warmer temperatures, which followed, allowed for their recovery and increased DM production. Turnip produced more TDM at 60 DAS, than any other crop and bean, the least. However, by the final harvest maize had the highest TDM and turnip (shoot DM only), the least. This was probably due to increased levels of intercepted PAR very early in turnip growth and development. This crop with its flat leaved canopy developed the highest early LAI (k – 0.85), achieving its critical LAI of 3.5 earlier than any other crop (50 DAS). Maize on the other hand, which has more erect leaves, had the second highest k value (0.84) and achieved its critical LAI of 3.5 at 90 DAS.

Increased weed emergence in all crops in the first 6 weeks from sowing was directly related to increased light availability. Turnip, which formed a dense canopy very early, decreased light availability to the understorey considerably reducing weed growth. Competition for light was therefore mainly responsible for some of the observed weed suppression. Forage rape leaves also formed a dense canopy but the weeds were not efficiently suppressed. This suggests that the rapid establishment of turnip ground cover could have been a factor, which contributed to their suppression of weed growth. Canopy closure was achieved at 50 and 80 DAS for the highest and lowest populations for turnips and 75 DAS and never for rape. This accounts for the considerable difference in the orthogonal contrasts between the suppression of weeds of these two crops at 60 DAS and at final harvest (Table 3.4). However, this reduction might also have been due to a number of other factors such as allelopathy or effects mediated by other organisms.

There was some evidence that allelochemicals from the break down of turnip crop residues could have contributed to weed suppression. The turnip residues may have released allelochemicals during their decomposition, which would have further suppressed weeds. Grundy *et al.*, (1999) have indicated that some crucifers have allelopathic potential.

Crop density appeared to have a significant effect on DM production up to 90 DAS ($p < 0.001$). However, by the final harvest there was no significant difference among densities for the different crops. Maize at final harvest (210 DAS) produced the highest amount of DM at 28.6 t DM/ha at 0.5 x optimum population and reached a maximum yield of 34.4 t DM/ha at 2.0 x optimum population at 130 DAS. Lupin produced 14.1 t DM/ha at the 0.5 x optimum population. Their highest yield was at 2.0 x optimum population at 19.5 t DM/ha (130 DAS). The least DM was produced by the turnip (shoot DM only), at 6.4 t/ha at 0.5 x optimum population and 7.4 t/ha at 4.0 x optimum population at final harvest. Lodging was extensive at 4.0 x optimum population in lupins at 120 DAS and in the maize at 135 DAS. This was probably caused by high winds, and contributed to reduced DM production. Herbert *et al.*, (1978) showed that under irrigation lupin had the potential to yield 20 t/ha of herbage DM and Ganeshan (1998) obtained 31.3 t/ha. Yamoah *et al.*, (1998) reported a DM yield of 25.4 t/ha for maize (cv. Janna) in Canterbury.

In addition to increased crop DM with increased plant population the LAI invariably increased from the 0.5 – 4.0 x optimum population. This resulted in reduced days to canopy closure at the 4.0 x optimum population in all crops. Turnip at 4.0 x optimum population achieved canopy closure 10 days before lupin, rape, ryecorn, maize and at 0.5 x optimum population of turnip. Increased LAI with increased plant population resulted in high total intercepted PAR, which enabled the plants to produce a high TDM by final harvest. At the lower plant populations the amount of total intercepted PAR was reduced which subsequently reduced the TDM production. The lower LAI at the 0.5 and 1.0 x optimum populations for lupin, rape, ryecorn, bean, maize and rape and ryecorn respectively in combination with an equally low total intercepted PAR resulted in lower TDMs in these treatments. Increased DM production with increased radiation interception has been reported in lentils (McKenzie *et al.*, 1989). A significant relationship was found by McKenzie *et al.*, (1989) with increased lentil DM production and intercepted radiation with increased crop population. This trend was similar to the crops sown in this trial with increased DM production at increased crop populations.

Yield and yield components: The increased plant population from 0.5 – 4.0 x optimum population significantly affected the grain yield through a highly significant crop x density interaction. The highest grain yields were attained at 0.5 x optimum population in lupin, ryecorn and maize where intraplant competition was lowest. The reduction in grain yield with increased plant populations in the lupin and bean could be accounted for by the extensive branching that occurred in these two species at low populations that increased pod production/plant. Lucas and Milbourn, (1976), Malone, (1978) and Owens y de Novoa (1980) all found that increased DM production at low plant populations was due to increased branching. At the same time there was increased leaf formation and a higher retention of formed pods than at higher densities in bean. This gave a higher grain yield. In maize, the number of cobs/plant was 2 (at 0.5 x optimum population) compared with only 1 cob at all other plant populations. Bean showed a similar trend where at 0.5 x optimum population the highest number of pods/plant was produced. The number of pods/plant ranged from 4.7 at the 4.0 x optimum population to 16.7 at the 0.5 x optimum population. The number of seeds/pod decreased with increased plant population. Grain yield increased with increased plants/m^2 up to 2.0 x optimum population in bean. Similar results were reported in lentils by McKenzie *et al.*, (1989) under the similar conditions.

Walton (1986) showed that at low plant populations, where weed competition was highest, the pod number/plant was reduced with the greatest reduction being on lateral branches. Other researchers (Wither *et al.*, 1975; Porter, 1982) indicated that when water stress occurs during flowering, lateral branch development is also limited. An increase in the crop density would further increase pod set on the primary stem suggesting that there is an interaction between crop density and plant development. However, Walton (1986) reported that increasing the lupin density did not produce significant yield increase, which is similar to the findings reported here.

Harvest index: The significantly lower HI at the 4.0 x optimum population was a result of high TDM production and a limited supply of assimilates for grain formation. The HIs obtained for the different crops in this study were high compared with reported HI for similar crops, except ryecorn. Maize for example produced its highest HI at 0.5 x optimum population. The result was comparable to values, attained by Millner *et al.*, (1996) of 0.46 at a plant population of 10 plants/m^2. At 2.0 x optimum population a HI of 0.36 was obtained. This was similar to the findings of Yamoah *et al.*, (1998) at high plant densities. The lower HIs at the higher plant densities was probably because of reduced net photosynthesis caused by early canopy closure and higher intraplant competition. The amount of photosynthate translocated into the sinks for grain filling can be reduced due to increased net respiration. This accounts for the decline in seed yield at the higher plant populations. Millner *et al.*, (1996) also reported a reduction in HI in maize with increased plant density.

Weed effects: After canopy closure from 60 DAS weed DM decreased with increased crop population in most crops. At high crop populations there was more interplant competition for light, water and nutrients. The combination of competition for both water and light at these higher crop populations would therefore result in severe competition to the weeds and give lower weed DM production.

There was little or no shading effect of weeds on the crops except at 0.5, and 1.0 x optimum populations in rape and particularly bean. These populations allowed the establishment and profuse growth of weeds. In these treatments weeds such as fathen (*Chenopodium album*), black nightshade (*Solanum nigrum*), Californian thistle (*Cirsium arvense*) and hawksbeard (*Crepis capillaris*) shaded the crop in some instances from onset of flowering to final harvest.

The fact that the presence of the weeds did not reduce the yield of the grain crops at the lowest densities may be evidence of facilitation (Radosevich *et al.*, 1996). Mixed species are likely to interact with each other by interference, according to the principles of plant physiology. However, the absence of yield depression at this density, where there is likely to be competition for light and the weeds were not effectively suppressed suggests that facilitation balanced the interference by counteracting the opposing tendencies. Increased population density suppresses weeds but evidence suggests that when moisture is limiting the grain yield suffers. This facilitation could be caused by improved water relations, allelopathy, or improved nutrient uptake.

Additionally, two other factors may have contributed to this yield increase. Firstly, most of the grain crops had a competitive advantage over the weeds because of their early establishment. Secondly, the dominant competing weeds, which were associated with these crop treatments, were not competitive weeds (scarlet pimpernel (*Anagallis arvensis*), twin cress (*Coronopus didymus*) and others).

Turnips were highly effective in reducing all weeds and this was probably due to the early high LAI produced by this species at all crop populations. This crop intercepted the most radiation at 4.0 x optimum population compared with the other crops in the trial and they achieved canopy closure at about 50 DAS. At 1.0 x optimum population this occurred at 55 DAS. Collie and McKenzie (1997) reported canopy closure at 58 DAS for turnips at this density.

The importance of early canopy closure from increased plant population is that it reduces the critical period for weed competition in the first 6 – 8 weeks after the sowing the crop. The time of canopy closure may determine the end of the critical period for weed competition with the crop. If increased plant population decreases the time to canopy closure then the critical period for weed control would be decreased.

3.5 Conclusions

- All the crops in this trial reduced weed productivity.
- The level of weed suppression among the crops was: beans < rape < ryecorn < lupin < maize < turnips.
- Morphologically different crops differed in their weed suppression.
- Increased plant population density may not increase crop grain yield, but it may improve the level of weed suppression.
- Weed pressure in this trial was insufficient to produce adverse competitive effects on the crops.
- The early establishment of crop ground cover reduced the chance of weed growth.
- The ability to suppress weeds was independent of crop growth habit, but was related to leaf size and plant growth rate.
- The inclusion of large leaf size and rapid growth in selection of crops as competitors to suppress weeds should be feasible in weed management.

Chapter 4

Evaluation of a mechanistic model of crop and weed growth

4.1 Introduction

Integrated weed management programs require reliable and quantitative predictions of the effects of weeds on crop yield. This may be achieved using empirical models that describe the response of crop yield to weed density and the relative time of emergence of the weeds with respect to the crop. Most of these models have described crop losses as a single function of one or several factors such as weed density, relative weed leaf area or the relative time of weed emergence (Cousens *et al.*, 1987).

Kropff *et al.*, (1992) and Lotz *et al.*, (1994) identified a number of limitations with regards to weed density being a good predictor of crop yield when weeds vary greatly in their size and/or relative time of emergence and development. Because weeds emerge in successive flushes and are quite patchy within a crop the relative time of weed emergence in relation to the crop is not always a useful concept (Brain and Cousens, 1990). Additionally, other factors such as crop density, crop cultivar and soil fertility are assumed to be constant and not important in these regression models (Christensen, 1995). To overcome these limitation, Spitters (1989), Kropff and Spitters (1991), Lotz *et al.*, (1992, 1994), Knezevic *et al.*, (1995), and Bourdôt *et al.*, (1997) have developed, mechanistic simulation models of weed-crop competition involving early prediction of the relative leaf area.

Empirical models of the crop/weed interaction often include general simulation models of crop growth that are modified to model the effect of particular weed species on crops. These models can be used as research tools to investigate the various factors that affect weed-crop competition, and to make predictions about crop yield losses that can then be tested in the field. In addition, these have shown limitations due to the lack of accurate, quick and non-destructive sampling methods to estimate the leaf area (Knezevic *et al.*, 1995).

More complex mechanistic models such as *Sirius* (Jamieson *et al.*, 1998) have been developed that calculate the biomass accumulation from intercepted solar radiation. It can provide realistic simulations of crop biomass growth and grain yield over a wide range of environmental conditions (Bourdôt *et al.*, 1999). Bourdôt *et al.*,

(1999) suggested the possibility of modelling and predicting weed biomass growth and seed yield in a similar way.

Non-destructive methods of obtaining leaf area and assessing ground cover quantitatively have been suggested by Kropff (1988), Lutmann (1992), Lotz *et al.*, (1994), and Ngouajio *et al.*, (1998). These methods involve the use of leaf cover obtained from the vertical projection of the canopy of individual species on the ground surface by the use of photography. Digital image analysis can be used for the determination of crop and weed leaf cover at an early stage in the plant's development. This non-destructive technique allows for a rapid and accurate method of measuring the growth rates by capturing a time series of the crop and the weeds without disturbing their development.

Crop and weed biomass accumulation can be modelled using crop and weed LAI and light intercepted during the growing season. To test this hypothesis the following objectives were planned to:

a) Investigate the utility of digital image analysis for the estimation of crop and weed leaf cover (early leaf area estimation), assuming that for the early growth stages the leaf area index of the weeds can be considered to be additional to that of the crop.
b) Test a simple computer based mechanistic model using independent field data on the growth of early sown crops of narrow-leaved lupin, ryecorn and forage rape and,
c) Use the model to evaluate the influence of crop and weed leaf area using comparisons with the measured biomass.

4.2 Materials and methods

The data presented in this chapter comes from the experiment described in Chapter 3 and is for the early sown crops sown on 8 September 1999:

Forage rape (cv. Giant rape) – (25, 50, 100 and 200 plants/m^2)

Narrow leafed lupin (cv. Fest) – (50, 100, 200, 400 plants/m^2)

Ryecorn (cv. Petkusier) – (125, 250, 500, 1000 plants/m^2)

4.3 Measurements

4.3.1 Image acquisition and analysis

Ground cover was measured non-destructively using digital image analysis. A program written by Wang Jian (1998) in Video Pro v3.1 was used for measuring the leaf area and ground cover of the crop and weed plants *in situ*. Six digital images were taken weekly with a Kodak DC 40 digital camera per plot on 4, 11, 18 and 25 October and 1 and 8 November 1999. This was at 26, 33, 40, 47, 53, and 60 days after sowing (DAS) respectively. Recording was stopped when the canopies closed.

The ground cover of crop and weed was measured weekly until the crop canopy closed. The digital camera was attached to a tripod for overhead photography and the image was taken 1 m vertically over an area of 20 x 30 cm (Plate 4.1). A bubble level was placed on the top of the tripod stand to ensure that the camera was level for each image. A plumb line was also attached to the camera with the weight just touching the ground to enable the camera to be positioned at the same height for each exposure. The images were taken under cloudy conditions or under an umbrella to avoid shadows. Images were then downloaded on to a computer. The number of pixels covering each species and soil was recorded to give an estimate of the percentage ground cover.

Plate 4.1. Digital camera used for taking digital images of crops.

Each digitised frame of the images measured 720 x 512 (368.640) pixels/frame. The pixels were spectrally analysed by a computer program that measured the vertical projected area. or ground cover (Wang and Bourdôt. 1997). Before running the analysis of the frames of each crop type. the program was 'trained' to distinguish between crop. weed and soil using red. blue and green colour information and to estimate their proportion of the total image area by a segmentation processes (Plate 4.2). This was then plotted on a histogram where thresholds were set as required to include or exclude hues of interest. Images were then manually touched-up to include or exclude plant leaves that were obscured or poorly defined. The software estimated the proportion of pixels that fell within these thresholds and then printed the result onto a screen or printer. The entire analysis took about 30 - 40 seconds/frame. The results are expressed as leaf length. area. or the number of units as defined (Hurrell. pers. comm.. 2000). Plate 4.3 shows digital images of ryecorn at 4.0 x optimum population at 3 – 8 weeks from sowing.

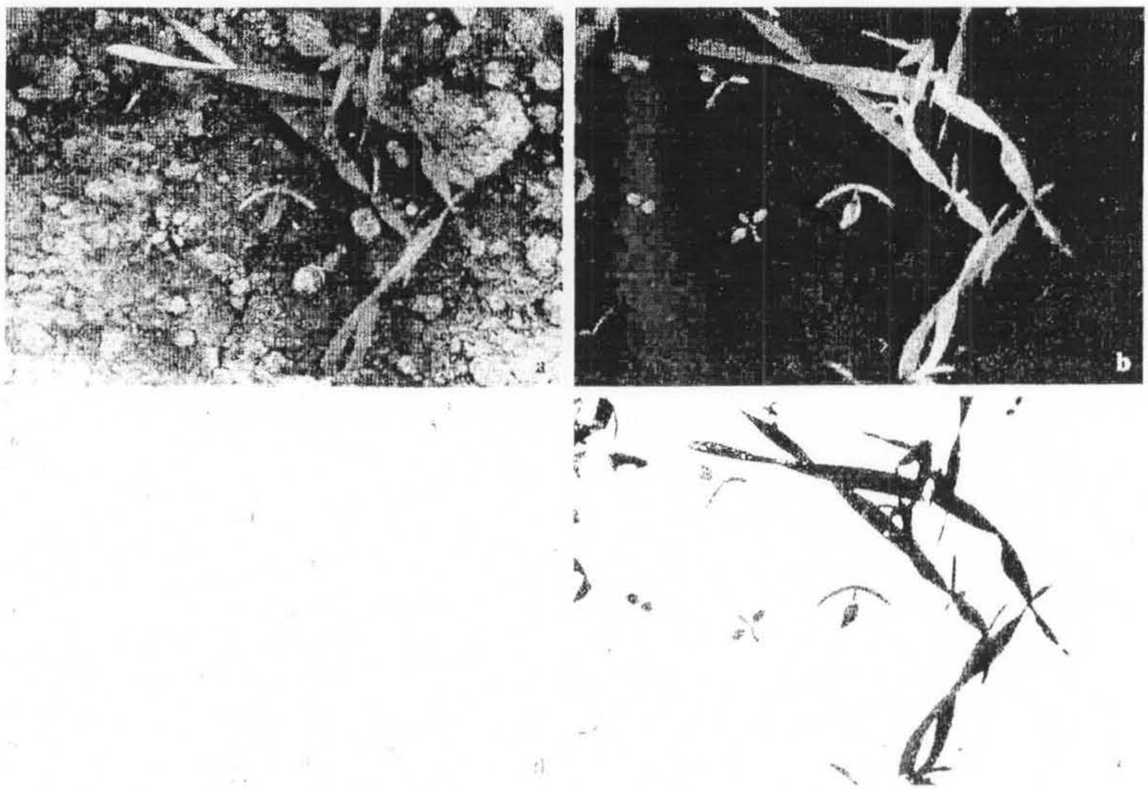

Plate 4.2: The four step procedure necessary to obtain the proportion of crop and weed pixels from computer software (a) green leaf material against soil background in picture frame of the computer program: (b) green leaf material: (c) image after thresholding: (d) segmented image.

Measured crop and weed DM values were obtained on 31 October 1999 for all crops (52 DAS). From 26 October, when crop canopy closure started, leaf area index (LAI) was recorded using a LICOR LAI 2000 Crop Canopy Analyser (LI-COR Inc., Lincoln, Nebraska, USA) on a weekly basis. Destructive DM samples were taken fortnightly from each plot from 31 October (52 DAS).

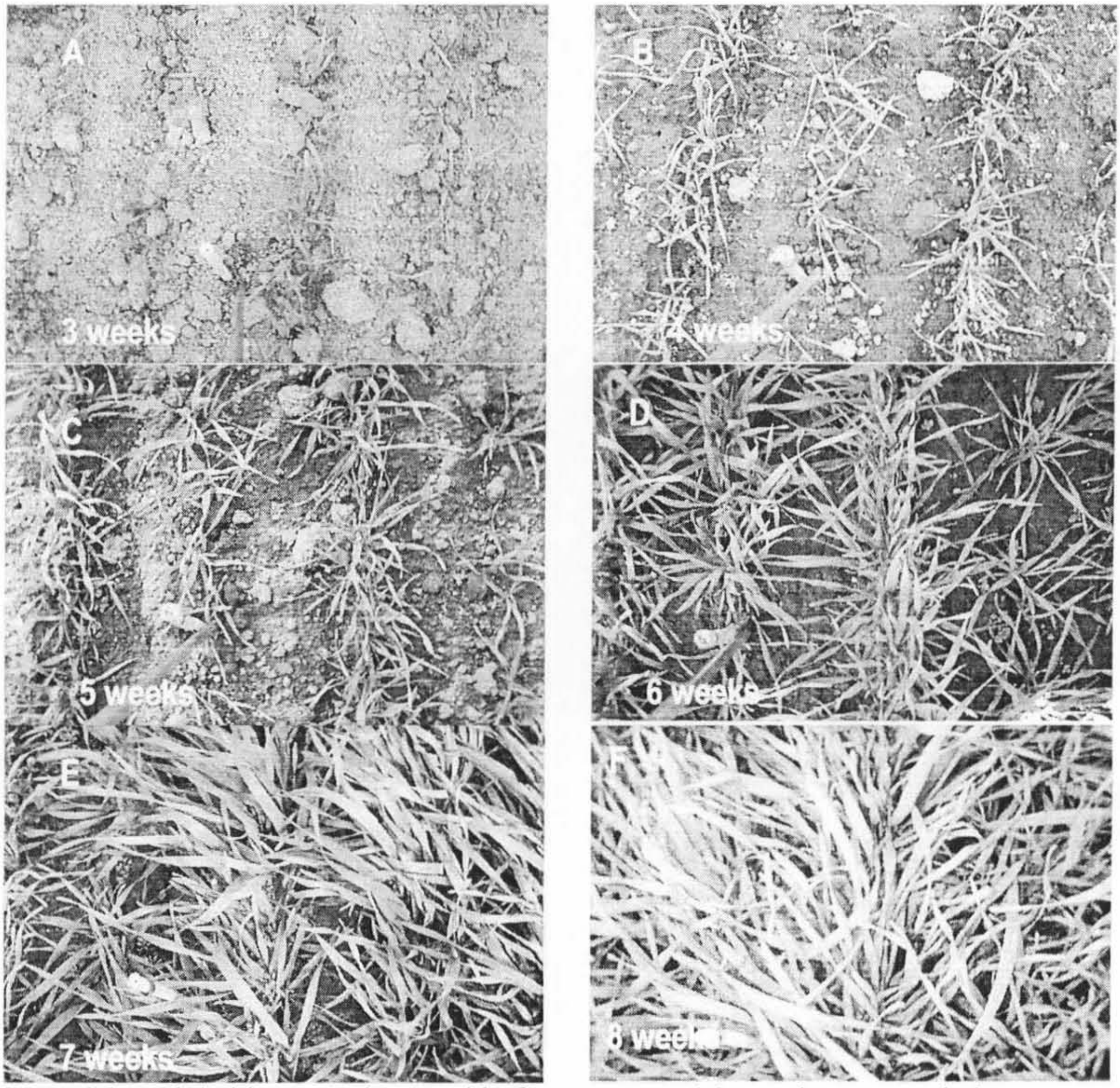

Plate 4.3: Digital images taken weekly for ryecorn at 4.0 x optimum population

4.3.2 Statistical Analysis

The structure of the mechanistic simulation model used in this evaluation has been described by Jamieson *et al.*, (1998) and Bourdôt *et al.*, (1999). The model simulates the seasonal growth in biomass of wheat and the weed community. The model presented here attempts to simulate biomass of the crop and weed from emergence through to crop maturity as a function of radiation, temperature, rainfall and species characteristics with a time step of 1 day.

In the model, crop (or weed) growth rate on each day of the growing season (*GR*) is as follows:

$$GR = 1.1 \times GC \times SR \text{ ....Equation 4.1}$$

where *GC* is the crop or weed ground cover (proportion of land covered when viewed vertically from above, i.e. the fraction of incident solar radiation intercepted by the crop) and *SR* is the daily solar radiation (MJ/m^2 per day). The crop growth rate depends on the amount of solar radiation incident on the crop canopy. The constant 1.1 represents the light use efficiency in units of g/MJ of total solar radiation (Jamieson *et al.*, 1998). The accumulated crop and weed biomass are given by the sum of the daily values of *GR*. The daily values of *GC* needed to simulate crop and weed growth for the period up until canopy closure were estimated from the digital images by linear interpolation between sample dates. From the time of canopy closure until the end of crop growth, when direct measures of *GC* could not be made, crop and weed *GC* were estimated from the Beer de Lambert law as:

$$GC = 1 - \exp(-k\ LAI) \text{ ....Equation 4.2}$$

where the *LAI* is the crop and weed leaf area measured as a fraction of the ground area occupied and *k* is the PAR light extinction coefficient for diffuse light. This depends on the canopy geometry and indicates how rapidly light is extinguished as it goes through the canopy. This value of *k* for the three crops studied was determined from the relationship between light transmitted through the canopy and LAI. Assuming that reflectance of the canopy was 0.06 (Kropff and van Laar, 1993):

$$k = -\ln(0.94 \text{ PAR transmission})\ \text{LAI}^{-1} \text{ ....Equation 4.3}$$

The simulated results were compared with the corresponding observed results. Predicted (P) and observed (O) values were used to quantify the root mean square deviation (RMSD) between a number (n) of predicted and observed paired results as follows:

$$RMSD = [(\Sigma(O - P)^2/n)]^{0.5} \text{.............................Equation 4.4}$$

The RMSD is a measure of the accuracy of the prediction and represents a weighed average difference between predicted and observed data.

Crop and weed DM were subjected to analysis of variance (ANOVA) using MINITAB 11.12 (1996) (as used in Chapter 3). Means were separated at the 5 % level of significance using least significance difference (LSD) for crop main effect and the crop by density interaction.

Calculated extinction coefficient: The extinction coefficient (*k*) values calculated by equation 4.3 for each crop were: - ryecorn – 0.45, rape – 0.43 and lupin – 0.79. Weed LAIs were estimated as a percentage of the total LAI from the *GC*. Varying *k* values were used in the model at each density ranging from 0.59 in 0.5 x optimum population of the three crops to 0.1 in the 4.0 x optimum population. The value of 0.59 for *k* was estimated from the no crop control. A value of 0.1 was estimated by Bourdôt *et al.*, (1999) for weeds in wheat and this value was used for ryecorn weeds.

4.4 Results

4.4.1 Ground cover from digital images

The proportion of *GC* from the digital images in the first 6 weeks from sowing showed similar trends to DM accumulation for the different plant populations for the 3 crops tested. Generally with increased plant population crop *GC* increased (Figure 4.1).

There were significant crop by density differences among the different crops ($p < 0.05$) for weed ground cover (Figure 4.2). In the lupins, there was a significant difference in weed *GC* among the different plant populations ($p < 0.05$). Lupin at 1.0 x optimum population had a higher proportion of *GC* than at the 0.5 x optimum population. Ryecorn at the 0.5 and 1.0 x optimum population were indistinguishable in their proportion of *GC*. However, at the 2.0 and 4.0 x optimum population there was a decrease in weed *GC*. The highest proportion of weed *GC* in the rape was at the 0.5 x optimum population. This proportion of *GC* then decreased for 2.0 followed by 1.0 and 4.0 x optimum population.

Comparative analysis among the different crop types at varying plant populations revealed that rape consistently had a higher proportion of *GC* regardless of plant population. This was followed by ryecorn and finally lupin. There were discrepancies at 1.0 x optimum population, where lupin and rape had similar *GC* proportions and ryecorn had the lowest proportion of weed *GC*.

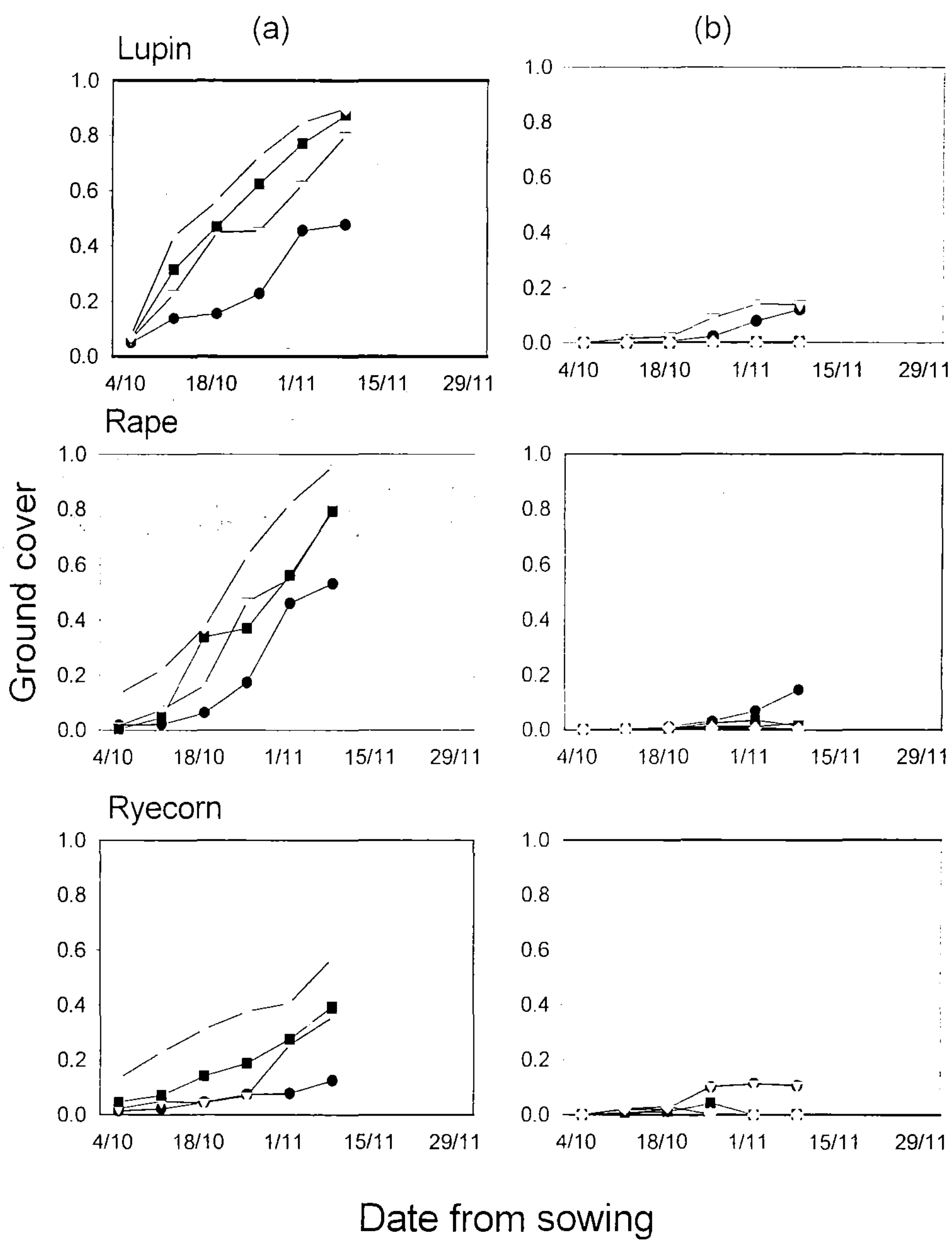

Figure 4.1. Ground cover (as a proportion) by (a) crop and (b) weed from the digital images over time from 26 – 60 days after emergence. 0.5 (●), 1.0 (▽), 2.0 (■), and 4.0 (◊) x optimum population.

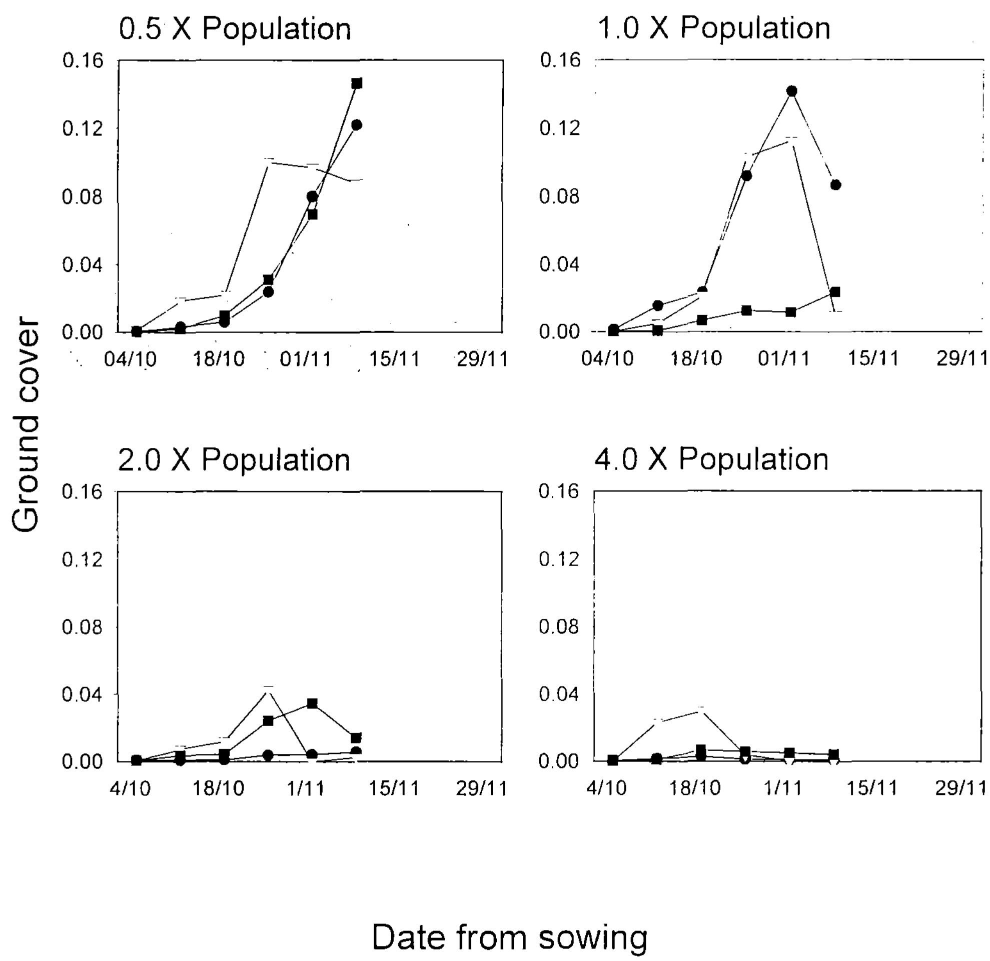

Figure 4.2. The proportion of weed ground cover from digital images for the three crops at four plant populations. Ryecorn (●), rape (▽), and lupin (■).

4.4.2 Crop DM accumulation

The model (Equation 4.1) accurately predicted crop DM production throughout the season (Figure 4.3). Lupins showed an almost perfect relationship with the predicted values at all populations. There were some variances in the mid October to early December period where the simulated values were higher than the actual values at 0.5 and 4.0 x optimum population. Simulated biomass accumulation for rape was also almost perfectly correlated at all populations. Rape at 4.0 x optimum population had the highest RSMD value of all the other plant populations (84 g/m^2). At 0.5 and 1.0 x optimum population ryecorn biomass simulation were also in close agreement with the measured values. There were discrepancies at 2.0 x optimum population where measured values were higher than predicted values from November to late mid December. At 4.0 x optimum population the predicted values were higher than the measured values from November to early December. Appendix 4 shows a run from the simulation model for ryecorn crop at 0.5 x optimum population.

Figure 4.4 shows the relationship between the simulated and measured DM for the three crops at all population densities. All relationships were highly significant with r^2 values of 0.95 for lupin and rape and 0.89 for ryecorn.

Lupins reached their highest maximum crop growth rate in early December which ranged from 34.9 – 36.2 g DM/m^2 per day for 0.5 and 2.0 x optimum population. Both rape and ryecorn ranged from 26.0 – 29.8 and 27.7 – 28.3 g DM m^2 per day. at 1.0 and 2.0 x optimum population respectively. There was no interaction among the different crops.

4.4.3 Weed DM accumulation

Weed DM was significantly reduced at sequential harvests with increased plant population in each crop ($p < 0.001$) (Chapter 3). In lupins. the increase in weed DM was simulated well by the model using varying *k* values with increased plant population. However. the simulation underestimated the weed DM accumulation in rape at 2.0 and 4.0 x optimum population as well as in the no crop control at all but the final harvest. The RSMD was 37.5 and 49.5 g/m^2 DM for rape at 2.0 and 4.0 x optimum population and 707.8 g/m^2 in the no crop control. At 1.0 x optimum population the simulation overestimated in ryecorn. Appendix 4 shows a run from the simulation model for ryecorn weed at 0.5 x optimum population.

Figure 4.5 shows the effect of crop density on the simulated and actual weed DM at 0.5 and 4.0 x optimum population. Predicted weed DM accumulation was accurate for lupin and ryecorn. However, it was less than actual DM accumulation in rape. There was a strong positive relationship between the observed and predicted weed DM in lupin ($p < 0.001$) ($r^2 = 0.96$) (Figure 4.6). However, the 1:1 line showed that the simulated values were generally underestimated. Both rape and ryecorn had weaker positive correlations between simulated and measured DM ($r^2 = 0.79$ and $r^2 = 0.68$ respectively). In rape the simulated values were underestimated and in ryecorn they were overestimated (Figure 4.6).

The predicted final weed DM was 25, 17, 3 and 0.5 % of that in the no crop control for lupin, 25, 10, 5 and 2 % for rape and 17, 18, 3 and 1 % for ryecorn at 0.5, 1.0, 2.0 and 4.0 x optimum population. There was a significant crop by density difference ($p < 0.05$) in the maximum weed growth rate. This was highest at 0.5 x optimum population and lowest at 4.0 x optimum population (10.2 versus 0.12 g DM m^{-2} per day for lupins, attained in early December, 8.8 versus 0.4 g DM m^{-2} per day for rape (at around the same time and 6.7 versus 0.4 for g DM m^{-2} per day in ryecorn (reached in late November). Overall, lupins had the highest weed growth rate followed by rape and ryecorn. A maximum weed growth rate of 36.2 g DM m^{-2} per day was achieved in the no crop control in early December. This was higher than in the crops.

4.4.4 *Ground cover*

As discussed in Section 4.3, the predicted *GC* (Equation 4.2) depended on the measured LAI from 26 October 1999. In the model, the development of *GC* from the point where LAI inputs were made proved to be difficult to simulate for lupin at all densities and for ryecorn at 1.0, 2.0 and 4.0 x optimum population. However, rape *GC* development was simulated quite well.

Figure 4.7 shows the relationship between the GC and the LAI for crop and weed for rape and ryecorn at 0.5 x optimum population. The model also accurately predicted the measured *GC* values at the corresponding LAI for the crop and the weed. The crop *GC* was much higher than the weed *GC*.

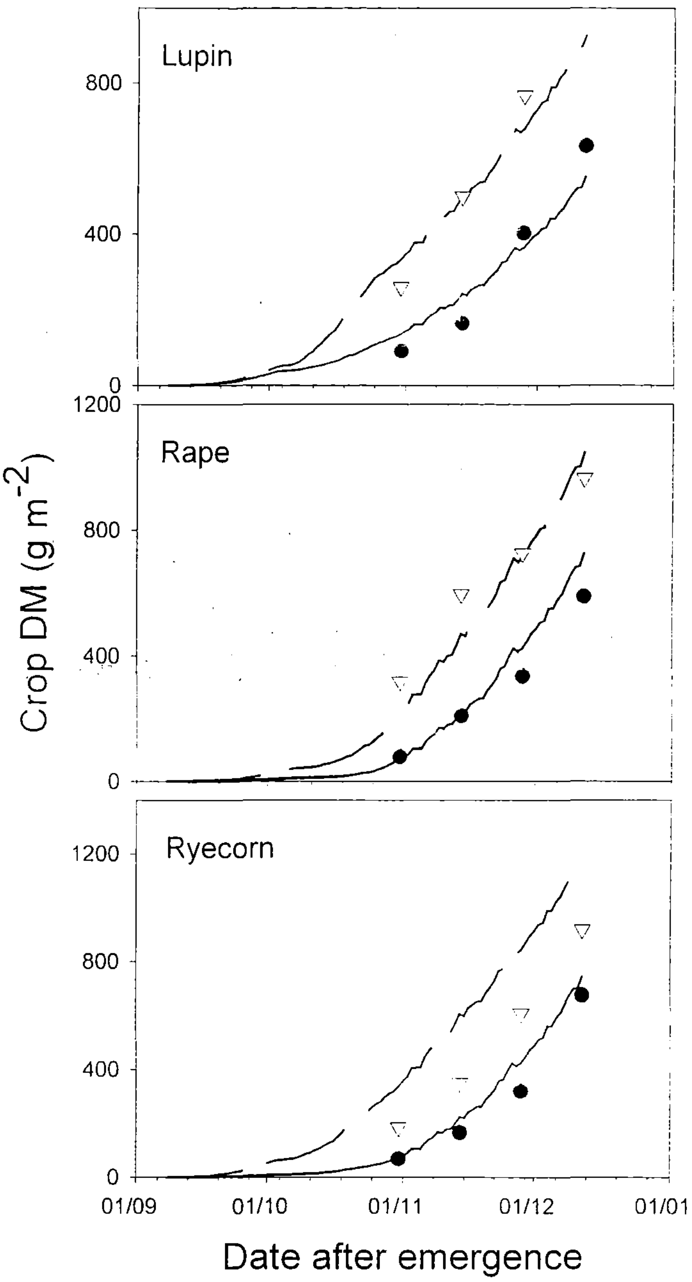

Figure 4.3. Simulated and measured crop dry matter (DM) accumulation for lupin. rape and ryecorn at the ● (0.5 x optimum population) and ▽ (4.0 x optimum population). Simulated DM (Equation 4.1) is given as curves.

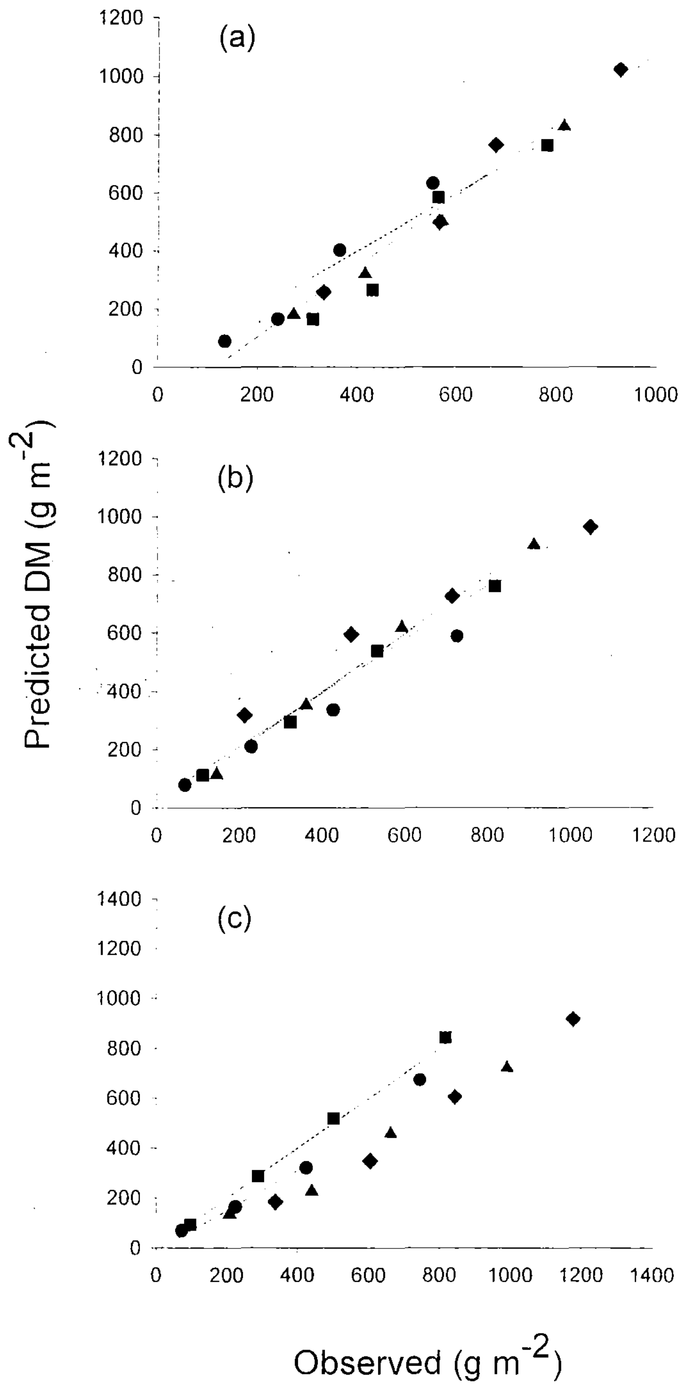

Figure 4.4. Observed versus predicted crop dry matter (DM) accumulation for three crops at four plant populations 0.5 (●), 1.0 (■), 2.0 (▼) and 4.0 (♦) x optimum population. The solid line is the regression and the dotted line is the 1:1 line.

(a) Lupin – $Y = -139.6 + 1.2\ x$ ($r^2 = 0.95^{***}$)

(b) Rape – $Y = 27.7 + 0.92\ x$ ($r^2 = 0.95^{***}$)

(c) Ryecorn – $Y = -9.1 + 0.80\ x$ ($r^2 = 0.89^{***}$)

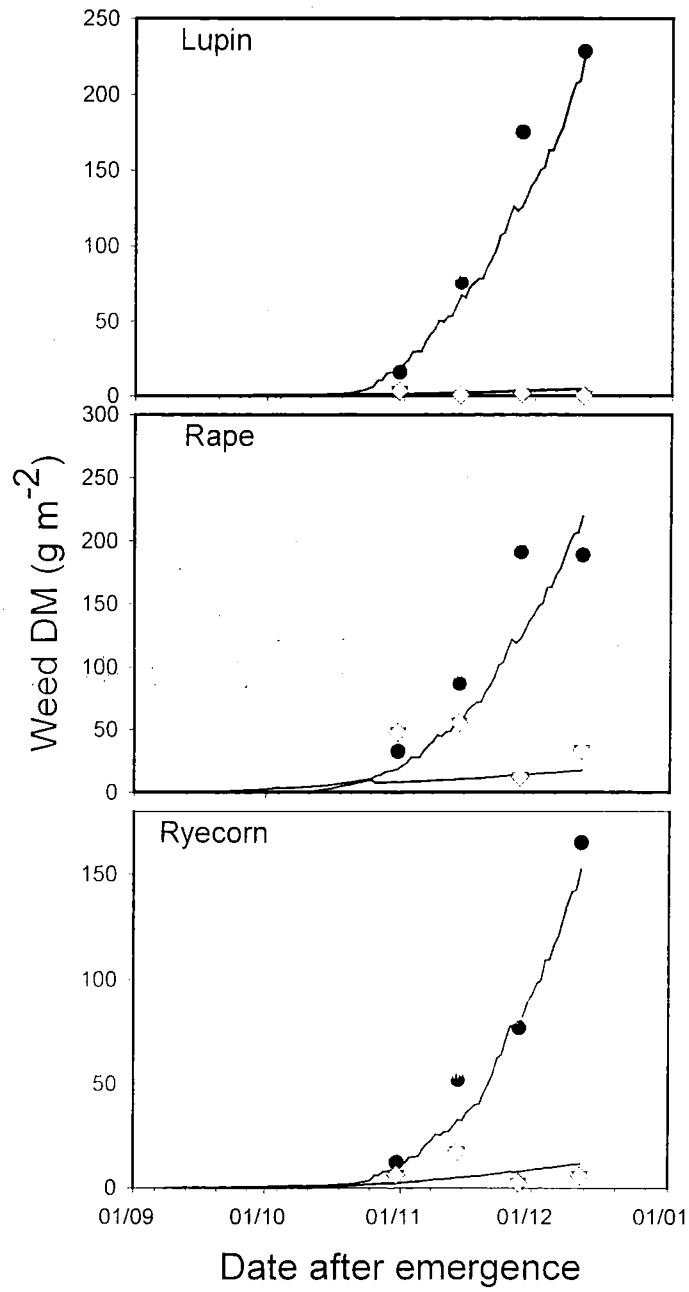

Figure 4.5. The effect of crop density on the dry matter (DM) accumulation of weeds. Measured DM is shown as: • (0.5 x optimum population) and ◇ (4.0 x optimum population). Simulated DM (Equation 4.1) is shown as curves.

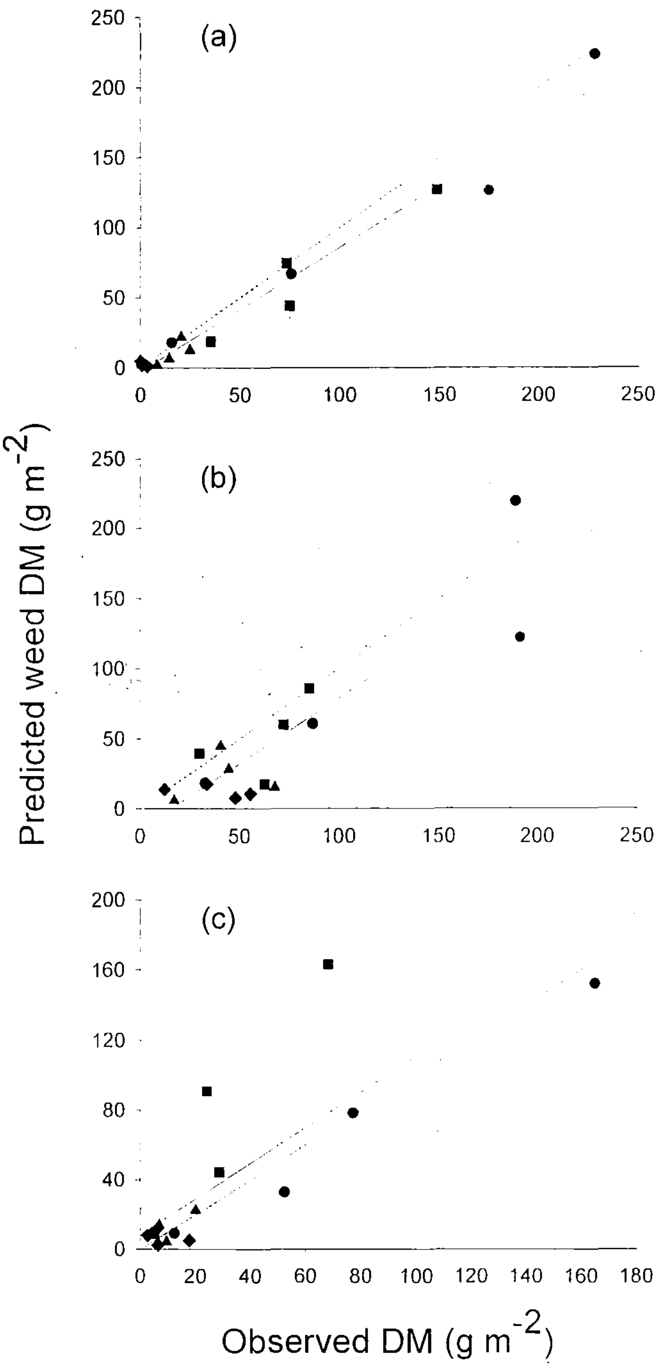

Figure 4.6. Observed versus predicted weed dry matter (DM) accumulation for (a) lupin, (b) rape and (c) ryecorn at four plant populations 0.5 (●), 1.0 (■), 2.0 (▼) and 4.0 (♦) x optimum population. The solid line is the regression and the dotted line is the 1:1 line.
(a) Lupin – Y = -2.9 + 0.89 x (r^2= 0.96***)
(b) Rape – Y = -14.5 + 0.94 x (r^2 = 0.76***)
(c) Ryecorn – Y = 8.8 + 1.0 x (r^2 = 0.68**)

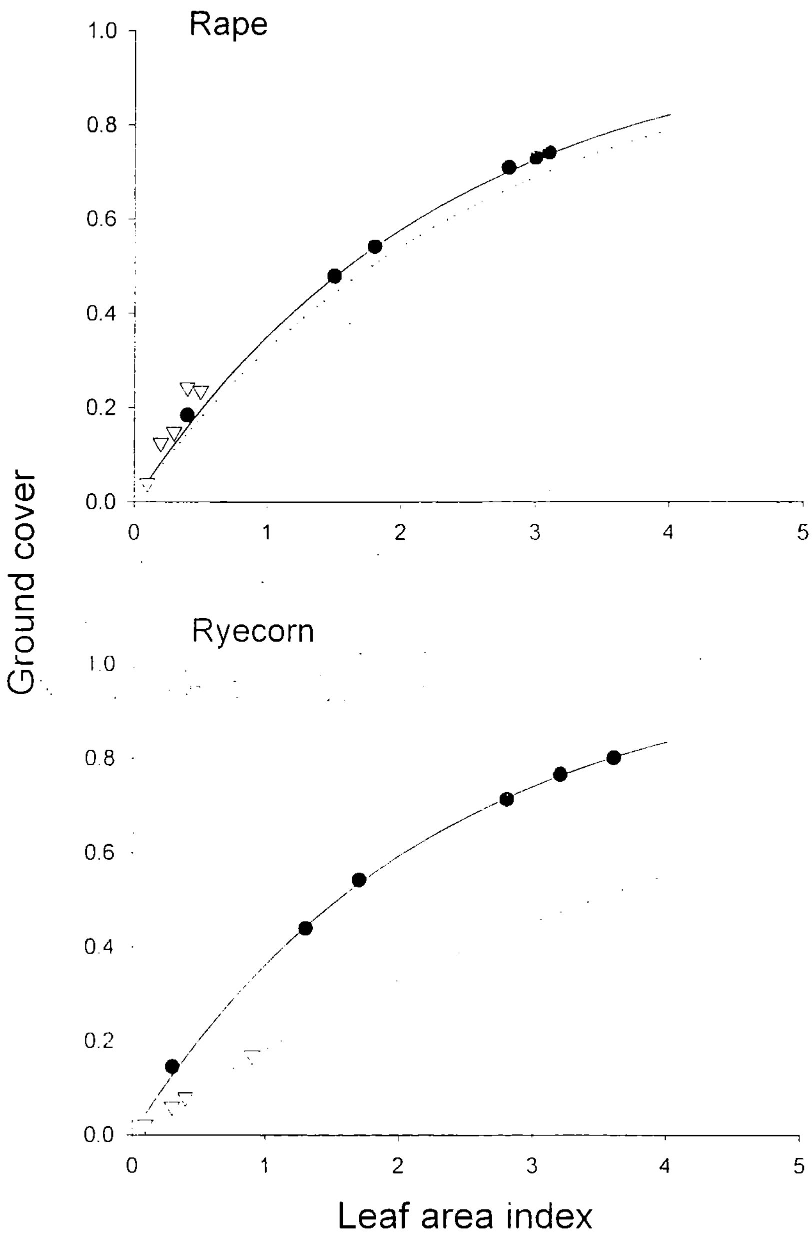

Figure 4.7. The relationship between ground cover (GC) and leaf area Index (LAI) for the crop and the weed for rape and ryecorn at 0.5 x optimum population. The solid line is simulated crop and the dotted line is the simulated weed using Equation 4.2. The actual values are crop (●) and weed (▽).

4.5 Discussion

4.5.1 Digital image analysis

Digital imaging may be a realistic alternative to obtain estimates of the early leaf area development of weeds and crops without the need for laborious destructive harvests, where the use of a canopy analyser is unsuitable. The results demonstrate that the use of digital imaging for *GC* estimation provided accurate data for the model up to the point where actual LAI values were measured for rape. However GC was a little underestimated for lupins at all densities and in ryecorn at 1.0, 2.0 and 4.0 x optimum population.

Only four *GC* values were used in the model as canopy closure of the different crops around the 5th and 6th *GC* estimations reduced the proportions of *GC* between the crop and the weed. Figure 4.2 illustrates this where reductions were observed on 25 October 1999 and on 1 November 1999 at the recommended population for rape and lupin respectively and earlier, on the 18 October 1999 in both rape and lupin at 4.0 x optimum population.

Unfortunately the technique has a slight bias in its inability to determine weed GC that may be covered by the crop GC when the crop leaf canopy overlaps with neighbouring weed species. The prospects for the use of digital imaging, however, may be improved by either increasing the plot size or by increasing the number of samples taken.

4.5.2 A mechanistic model for crop growth

The extinction coefficient (*k*) values used in the model for each crop of 0.45 for ryecorn, similar to that of wheat (0.46) (estimated by Thorne *et al.*, 1988); rape at 0.43 similar to that of radish (another rosette plant) of 0.30 – 0.42 (cited by Hay and Walker, 1989) and lupin at 0.79 similar to the 0.6 – 0.89 reported by Hay and Walker (1989) and 0.78 reported by Ayaz (pers. comm., 2000) for similar crop types all allowed the model to give a good fit for simulated DM accumulation.

The mechanistic model approach used in this experiment for the simulation of DM accumulation is based on very simple descriptions. Nevertheless, the model mimicked substantial variations of DM accumulation for lupin, rape and ryecorn at varying densities as well as the weeds (with a few minor adjustments). It also gave insights into the reasons for variations in performance of the different crops. It did this without any input of values for temperature, nitrogen, water, components of yield or other contributory factors. The discrepancies in the model where underestimations and overestimations were observed for ryecorn, at different densities, by the different crops were probably due to a number of reasons.

In ryecorn where the predicted values were higher than the measured the variations were probably the result of a heavy infestation of rust (*Puccinia graminis*) that affected the crop growth rate and hence crop DM production during November and early December. The higher measured DM value during the same period at the 2.0 x optimum population was probably due to an overestimation of DM in harvest collection procedures as the rust infestation had also affected this plant population. However, the model's predictions of DM accumulation for this crop were reasonably accurate in view of the fact that the crop was not vernalised.

4.5.3 A mechanistic model for weed growth

The increase in weed DM was simulated well by the model at 0.5 and 1.0 x optimum population for all crops using the k = 0.59 value that was calculated from the weeds in the no crop control. Manipulating the k value for 2.0 and 4.0 x optimum population by reducing it to 0.30 and 0.1 respectively gave a better fit. Bourdôt *et al.*, (1999), utilised a value of k = 0.1 for weeds in wheat in a similar model. Thorne *et al.*, (1988), mentioned that this value of k is small in comparison with wheat and a number of other grasses, and is much lower than the measured 0.59 in this experiment. Bourdôt *et al.*, (1999), justified this k value because the dominant weed species had small tubular leaves (*Stachys arvensis*) or leaves that stacked up on each other (*Veronica persica* and *Chenopidum album*).

Weeds present in the weed community in this trial included *Corynopus didymus*, *Anagillis arvensis*, *Trifolium repens*, and *Capsella bursa-pastoris*, in high proportions (including others listed in Table 5.3). These weeds have a more spreading growth habit and their leaves are not stacked up on each other. Hence the k values should be higher as calculated values indicate in the no crop control. Because morphologically different crops were used in this trial, the morphologies of the existing weeds varied greatly at all densities (Appendix 5). With increased plant populations the weed species grew taller and etiolated in an attempt to increase their competitive abilities with the crop canopies. At the lower plant populations of 0.5 and 1.0 x optimum population, weed growth was similar to the no crop control weed growth, hence the same k value was used. At the higher plant populations, crops and weeds competed strongly for light and the weed *k* values were probably lower. The competition was confirmed by the substantial reduction in weed DM accumulation as crop plant population density increased.

Crop and weed growth were modelled based on light interception through the canopy. With increased plant population, the LAI increased. This reduced the light transmitted through the canopy to the weeds below. Weed DM accumulation was therefore decreased with increased crop density as reported in Chapter 3. The more rapid canopy closure and higher LAI of the higher plant populations (2.0 and 4.0 x optimum population) induced competition for light at an earlier stage. The different *k* values used in the model, which were estimated based on the inclination or morphology of the leaves and the shape of the canopy for the different crops, showed variations in the accumulation of DM and the radiation use efficiency even though the LAI's were similar. This is because planophile or horizontally oriented leaves such as rape in the early stages of their growth capture light with a higher efficiency than erectophile or vertically oriented leaves, such as in ryecorn (de Wit, 1965).

4.6 Conclusions

- Digital image analysis gave a good estimation of the early sequential leaf area development of the crops and the weeds.

- Ground cover development, which was dependent on LAI values, was predicted quite well for the crops but not for the weeds.

- The results showed that DM accumulation of the different crops can be modelled mechanistically from the amount of radiation they to intercepted during the growing season.

- Weed DM accumulation with increased crop population also showed a concomitant decrease as obtained in the results reported in Chapter 3. Therefore it could also be accurately modelled mechanistically using LAI.

- Weed-crop competition can be modelled by combining solar radiation interception models.

- The model has shown its potential usefulness as an analytical tool for linking LAI to plant population increases and the competitive effects of crop species at varying densities on the DM accumulation of weed species. However, it needs further inputs, testing and validation to be developed into a more complex model.

Chapter 5

The effect of crop morphology and density on the species composition of a weed community

5.1 Introduction

Environmental concerns over excessive use of herbicides in recent years have prompted studies on the effects of crops on weeds. This research has generally examined agronomic factors such as the use of competitive cultivars or altering sowing dates. The majority of studies on crop-weed competition have focused on the relative effects of the weed on crop yield. Few studies have tested the effect of crop morphology and density on the abundance, productivity and species composition of associated weeds over time.

A possible strategy to enhance weed seed bank depletion is crop choice. This is because a crop canopy can affect weed emergence (Dotzenko, *et al.*, 1967; Anderson, 1998). For example, in one study, wild oat (*Avena fatua*) emergence during the growing season was less in barley (*Hordeum vulgare*) than in spring wheat (*Triticum aestivum*) (Thurston, 1962). However, volunteer wheat emergence during September and October has been shown to be three times greater in corn (*Zea mays*) than in proso millet (*Panicum miliaceum*) (Anderson and Nielson, 1996).

A possible advantage of increasing crop plant population is that it may exclude or suppress weeds more effectively. It is possible that increased crop plant population uses the available resources more completely and thus leaves less opportunity for the establishment and growth of weeds.

Soil weed seed banks are an important aspect of the dynamics of weed populations. Knowledge of them is of major importance for the selection of crops, rotations or chemical weed control. The effect of a crop on the composition and density of weed seed banks has not been as well documented (Belo and Dias, 1998) as the effect of herbicide use on weed seed banks (Roberts and Neilson, 1981). Teasdale (1995) noted the need for research on the differential response of important weed species to the sowing of crops at high populations. There is also a need to investigate whether the influence of high crop populations on weed seed production differs from their influence on weed growth.

Based on the hypothesis that different crops may affect weed species composition differently and that fewer, smaller weeds will result from increased relative sowing density of a crop, the following experiment was conducted using soil seed bank enumeration techniques and weed surveys.

The major objective was to:

- Determine the changes in weed flora over time by analysing buried weed seed and weed seedling emergence during the 1999/2000 and 2000/2001 growing seasons to obtain an indication of the likely population dynamics of weed species as influenced by crop type.

5.2 Materials and methods

Weed measurements were taken during the 2000/2001 growing season in each of the treatment plots from the previous year's trial (Chapter 3). After final sampling the lupin, ryecorn, maize and beans that remained on the field were harvested using a plot harvester. Sheep were then used to graze the remaining stubble and the area was topped with a mower. A forage harvester was used to remove all the remaining vegetation. Finally, 90 kg/ha of oats (*Avena sativa*) was direct drilled over the entire area to prevent the establishment of winter weeds.

Before weed measurements were taken in the 2000/2001 growing season sheep were again used to graze off the oats and other herbage on 4 September 2000. On 15 September 2000 each of the early sown plots from 1999 were top worked by cultivating the soil surface twice with a rotary hoe and they were then rolled. This was repeated on 2 November 2000 for the late sown plots and weeds were allowed to emerge.

5.2.1 Measurements

Soil seed bank and seedling emergence counts: The composition of weeds in the soil seed bank for the area of the trial was estimated using a sieving/floating technique.

Extraction method – (physical sieving/floating technique): In this method 60 soil samples were taken using a 15 mm diameter soil auger across the trial area. Samples were taken to a soil depth of 150 mm in the week prior to initial cultivation in August

1999. The samples were taken randomly from the field and were stored in plastic bags at room temperature. The samples were then passed through a 6 mm screen to remove large debris and to break up soil peds. Samples were then passed through a series of sieves to remove the debris and subjected to vigorous washing under a tap. The samples were then air-dried and were passed through a series of descending sieves. Individual weed seeds were extracted by hand, identified to species by placing under a 10 x magnification microscope and counted.

In September 2000 after the winter following the harvest of the crops another weed seed bank analysis was done. From each plot 10 soil cores were taken using the same soil auger to a depth of 50 mm. The soil samples were air dried for one day, adjusted to a weight of 200g and then placed in a fine mesh bag and subjected to vigorous washing to remove debris and soil. Samples were again air dried and passed through a descending series of sieves. Individual seeds were extracted by hand: identified to species under a 10 x magnification microscope and counted. Seeds that resisted gentle pressure with fine–tipped forceps were considered viable and were recorded.

Weed plant measurements: In the September and November 1999 sowings two fixed quadrats ($0.25m^2$) were randomly marked out with stakes in each plot. From these fixed quadrats weed observations were recorded weekly from 3 weeks after sowing to canopy closure.

At 52 days after sowing (DAS), destructive weed samples were taken from each crop treatment including the no crop control. The weeds were dissected by taxa (species or genus, depending on their similarity). Uncommon taxa were pooled. After drying, the dry weights were recorded. Samples were harvested from 0.25 m^2 with hand clippers, were cut to ground level and dried to constant weight at 70 °C for 24 h in a forced draught oven. This was done fortnightly until the final harvest of each crop was taken. Final samples for dry matter determination were taken from $1m^2$.

During the winter (July 2000) the weed flora was identified and weed seedling counts were made of the different weed species present from three $0.1m^2$ quadrats in each plot.

During the 2000/2001 growing season soil cores were taken just after the sheep grazed off the oats but before the soil was cultivated. On 16 October 2000 (58 weeks after the September 1999 sowing) weed seedling counts were taken and the weed species present were identified. This was repeated on the relevant plots 58 weeks after the November 1999 sowing on 14 December 2000.

The weed seedling counts were taken from three 0.25 m^2 fixed quadrats that were randomly placed toward the centre of each plot to avoid edge effects from overlapping. Overlapping may have occurred from the movement of weed seeds from adjacent plots during rotary hoeing.

5.3 Data analysis

For the weed seed bank analysis all the seed counts in September 2000 were adjusted to estimate the number of weed seeds per m^2 (to a depth of 50 mm) from the 200 g of dry soil sample collected.

The data was analysed as a randomised complete block design using analysis of variance (ANOVA) procedures. Means were compared using Fisher's Least Significant Difference (LSD) test at the $p < 0.05$ level.

The seed density estimates of individual weed species, derived from the soil seed bank enumeration, and the seedling emergence procedures were analysed with ANOVA. This was done to determine the usefulness of each seed estimation procedure for the elucidation of changes in seed density due to crop treatments.

Correlation coefficients of seed density estimates from the two estimation procedures (soil seed bank and weed seedling counts) were calculated. This allowed a comparison of the suitability of each technique for the determination of the abundance of individual weed species in the seed bank.

Weed seed bank estimates obtained by seed extraction from the soil core samples were correlated with the weed seedling counts made in the field in October and December 2000. Seed bank estimates were correlated with both weed seedling counts after their conversion to weeds/m^2. The field emergence percentage was estimated by dividing the density of seedlings emerging in the quadrats by the corresponding density counted by the extraction method. Correlation coefficients were also calculated for the relationship between weed seedling density in the field and estimates by the extraction method.

To detect differences in the weed communities among the different crop treatments, species dry matter (DM) yield data from each treatment were subjected to multivariate analysis. This analysis was attempted for the weeds that emerged in the 1999/2000 growing season. The advantage of this approach is that it allows comparisons using all weed species as variables in the analysis (Derken *et al.*, 1993). Principal component analysis (PCA) summarises data variation in terms of derived component axes. The first component axis explains the greatest proportion of linear variation in the data, while the second axis explains the next greatest proportion of the variation.

If the data are highly structured, the first few principle component axes will explain most of the variation in the data and thereby capture the underlying data trends (Manly, 1994). In this study, PCA was performed on the weed biomass data (using a correlation matrix) using the MINITAB 11.12 (1996) program. The ordination biplots generated by PCA are two–dimensional representations of crop treatments and the weed biomass contained within each treatment superimposed on the crop treatment. Every treatment appears as a letter on the biplot. A total of 10 weed species was included in the multivariate analysis. Other weed species occurred at very low proportions and they were not included in the analysis.

5.4 Results and discussion

5.4.1 Soil seed bank analysis

Weed seed bank (August 1999 prior to soil preparation): The weed seeds present in the soil seed bank before the trial began in September 1999 are listed in Table 5.1. Although the area was predominantly in *Trifolium repens* prior to sowing *Coronopus didymus* was the predominant weed seed species in the weed seed bank across the entire trial site.

Weed seed bank (2000/2001 growing season): Weed seed bank enumeration of soil cores taken in September 2000 prior to soil preparation showed a highly significant difference among the different crop treatments ($p < 0.001$) (Table 5.2, 5.3). The average lupin treatments had up to 158 x 10^3 seeds/m^2 (to a depth of 50 mm). This accounted for 12 % of the total weed seeds found in the early treatment plots. Rape (11 %) and ryecorn (9 %) followed. In the late sown treatment plots bean accounted for 22 %

followed by maize (11 %) and turnip (9 %). The early and late no crop controls accounted for 68 % and 58 % of the weeds in the weed seed bank respectively.

Generally weed seed number, which reflected the previous cropping history (1999/2000 growing season), showed a highly significant ($p < 0.001$) decrease with increased crop density in all crops. There were a few exceptions. In turnip plots the seed number/m^2 of soil decreased from 0.5 to 1.0 x optimum population and then increased from 2.0 to 4.0 x optimum population (56, 37, 54, 72 x 10^3 seeds/m^2) (Table 5.3). Lupin produced 197 x 10^2 seeds/m^2 of soil at 0.5 x optimum population and this increased by 86 x 10^2 seeds/m^2 at 1.0 x optimum population and then decreased. Rape had the highest number of seeds/m^2 of soil at 0.5 x optimum population of all the crops. It was followed by bean, lupin, ryecorn, maize and turnip (294, 288, 197, 127, 94 and 56 x 10^2 seeds/m^2 respectively) (Table 5.2, 5.3). In the no crop control, early sown plots had 29 % more seeds in the soil seed bank than the late sown plots. Crop treatments also showed this disparity by as much as 75 % between total weed seeds found in crop plots for the early and late sown crop treatments.

Table 5.1. The percentage composition of weed seeds, by species, in the soil seed bank to 150 mm before cultivation in September 1999.

Weed seed species	Composition (%)
Anagallis arvensis	9.0
Aphanes sp.	5.0
Brassica sp.	0.2
Chenopodium album	8.0
Cirsium spp.	0.1
Coronopus didymus	60.0
Poa annua	1.0
Polygoum aviculare	2.0
Silene gallica	0.9
Solanum nigrum	2.0
Spergula arvensis	2.0
Stellaria media	0.8
Taraxacum officinale	1.0
Trifolium repens	13.0
Veronica sp.	1.0
Viola sp.	2.0

The reason for the disparity in seed numbers was because there was a considerable interval after the final harvest of the early sown crops and that of the late sown crops. This might have contributed to the growth and development of many weed species. Further, during this period most of the lupin and ryecorn DM was removed. This may have significantly contributed to recruitment of weed seeds into the weed seed bank as much of the soil was left bare giving the opportunity for weeds to mature and set seed. The rape crop, which was the earliest crop to be harvested, was allowed to remain intact in plots. Most of the foliage however had already senesced thus allowing weed establishment in the rape plots, particularly at 0.5 x optimum population where the crop was poorly established. This accounts for the high weed seed number at this density.

Overall, turnip plots had the least number of weeds followed by maize, ryecorn, bean, rape and lupin. Weed seeds/m^2 soil in turnip however, increased in number from 1.0 to 4.0 x optimum population.

Weed seed output reflected the reproductive potential of the different weed species. This was determined by the competition experienced in the previous season (1999/2000 growing season). With increased competitive pressure exerted by crop treatments, the DM/plant for each weed would be reduced and consequently the weed seed number/plant (Kropff *et al.*, 1996).

Twenty potentially viable weed seed species were recorded in quantities ranging from 1 to 518 x 10^3 seeds/m^2 for individual weed species in the control plots. Under previous crop treatments of rape and bean at 0.5 x optimum population there were 1 to 82 x 10^3 seeds/m^2.

The major weed species seed found are listed in Table 5.4 (indicated by an asterisk*). *Coronopus didymus* (30.0 %) continued to dominate the weed seed bank followed by *Anagallis arvensis* (18.0 %). *Chenopodium album* (12.0 %), *Spergula arvensis* (11.0 %), *Silene gallica* (6.3 %) and *Capsella bursa-pastoris* (6.2 %). The seed numbers of these weed species are summarised in Table 5.2 and 5.3 for the early and late sown crops.

Coronopus didymus, which comprised 30 % of the weed seed bank in September 2000, was the third most prevalent weed in the previous season. There was no difference among the different crops for *Coronopus didymus*. However, there was a significant density effect ($p < 0.05$). In lupin and ryecorn plots, there was a decrease in *Coronopus didymus* numbers with increased crop plant population. There was some variability in *Coronopus didymus* seed production among rape, bean, turnip and maize plant populations. Overall, the seed numbers in the 0.5 and 1.0 x optimum population plots were higher than in the 2.0 and 4.0 x optimum population plots for lupin, rape and ryecorn.

There was a significant crop x density interaction ($p < 0.001$). Ryecorn plots had the lowest number of *Coronopus didymus* seeds (16×10^2 seeds/m^2) compared to rape, which contained the highest, number (35×10^2 seeds/m^2). This weed has been estimated to produce between 16,000 and 18,000 seeds/plant in Australia (Holm *et al.*, 1997).

Yields of 900 seeds/plant have been reported in fields in England for *Anagallis arvensis*, which was the predominant weed in the previous season. However, as many as 250,000 seeds/plant have been reported in the greenhouse (Holm *et al.*, 1977). The occurrence of *Anagallis arvensis* seeds was significantly different for crop treatments ($p < 0.001$). Lupin plots contained the most *Anagallis arvensis* seeds and accounted for 10 % of the total weed seeds found in the trial area followed by rape (8 %), ryecorn (8 %), bean (4 %), maize (1 %) and turnip (1 %).

There was also a significant density effect ($p < 0.05$) for *Anagallis arvensis*. Lowest seed numbers were found in the 4.0 x optimum population plots for all crop treatments except rape, bean and maize. In lupin and ryecorn *Anagallis arvensis* seed numbers decreased with increased plant population ($62 - 10 \times 10^2$ and $26 - 13 \times 10^2$ seeds/m^2 respectively from 0.5 to 4.0 x optimum population). There was also a significant crop x density interaction for *Anagallis arvensis*.

Table 5.2. Weed seed numbers x 10^3 /m^2 in September 2000 for early sown crops (lupin, rape, ryecorn).

Crop density	*C. didymus*	*A. anagallis*	*C. album*	*S. arvensis*	*S. gallica*	*C. bursa - pastoris*	Broadleaves	Grasses	Total
No crop control									
0.0	518	188	8	52	8	43	878	2	880
Lupin									
0.5	59	62	12	15	6	8	196	1	197
1.0	33	49	68	29	58	25	283	1	283
2.0	31	21	4	4	5	1	94	1	94
4.0	15	10	9	9	6	3	59	0	59
Rape									
0.5	82	64	29	45	12	4	293	1	294
1.0	43	32	9	13	8	11	145	0	145
2.0	6	57	13	4	3	3	64	0	64
4.0	8	12	8	9	6	5	58	2	60
Ryecorn									
0.5	19	26	9	14	8	35	126	1	127
1.0	27	52	18	11	10	13	148	0	148
2.0	10	21	9	11	7	4	74	0	75
4.0	9	13	13	7	7	5	64	1	65
Significance									
Crop x Density	***	***	NS	NS	***	NS	***	**	***
SEM	24	19	12	14	4	23	54	1	54
CV (%)	77	104	101	122	61	195	539	72	53

NS, non-significant; **, $P < 0.01$; ***, $P < 0.001$. Crop density – 0.5, 1.0, 2.0, and 4.0 x optimum population. Total = Broadleaved + Grasses

Table 5.3. Weed seed numbers x 10^3 m^2 in September 2000 for late sown crops (bean, turnip and maize).

Crop density	*C. didymus*	*A. anagallis*	*C. album*	*S. arvensis*	*S. gallica*	*C. bursa-pastoris*	Broadleaves	Grasses	Total
No crop control									
0.0	107	65	50	65	7	20	343	2	345
Bean									
0.5	19	35	67	37	8	69	285	30	288
1.0	22	5	7	6	11	10	81	10	82
2.0	5	4	18	7	4	6	63	10	63
4.0	23	7	16	14	12	0	86	10	86
Turnip									
0.5	2	4	12	16	4	2	55	10	56
1.0	3	4	9	4	4	4	36	10	37
2.0	16	6	7	14	5	7	54	0	54
4.0	97	1	12	6	6	4	71	10	72
Maize									
0.5	31	4	23	10	9	2	92	20	94
1.0	23	3	22	6	10	5	90	10	91
2.0	5	3	9	7	5	6	39	0	39
4.0	11	7	4	6	5	0	38	0	38
Significance									
Crop x Density	***	***	NS	NS	***	NS	***	**	***
SEM	24	19	12	14	4	23	54	10	54
CV (%)	77	104	101	122	61	195	53	72	53

NS, non-significant; **, $P < 0.01$; ***, $P < 0.001$. Crop density – 0.5, 1.0, 2.0, and 4.0 x optimum population. Total = Broadleaved + Grasses

Although *Chenopodium album* pre sowing seed numbers seedling counts and DM production were not high in the previous growing season (1999), there were high viable seed numbers in September 2000. There was no significant crop or density effect for *Chenopodium album*. The high *Chenopodium album* seed numbers could be accounted for by the high potential this weed has to produce seed. Up to 500,000 seeds on large plants. When grown with crops such as potatoes and sugar beet (*Beta vulgaris*), it can produce up to 13,000 seeds/plant (Holm *et al.*, 1977). Ghersa and Roush (1993) estimated that *Chenopodium album* has the potential to produce enough seed to overcrowd a 5 dm^2 module in one cycle of reproduction by producing 13,000 to 500,000 seeds/plant. Additionally, *Chenopodium album* seeds can survive for 30 to 40 years in the soil, as many of the seeds, which fall from the plant, may remain dormant.

Spergula arvensis seed were also found in large numbers. A large plant of this species has the potential to release 7,500 seeds. This weed did not show any significant difference in seed numbers among crop treatments but there was a significant density effect ($p < 0.05$). The highest amount of *Spergula arvensis* seed was found in the 0.5 x optimum population plots for all crops. However, there was some variability in seed numbers of this weed at other plant populations. Only ryecorn showed a decrease in *Spergula arvensis* seed numbers with increased plant population. There was no significant crop x density interaction.

Spergula arvensis grows with equal vigour in crops such as wheat, potatoes (*Solanum tuberosum*) and oats (Holm *et al.*, 1977). In seed production studies by Lemieux *et al.*, (1984) interspecific competition increased seed yield/plant and decreased other weed seeds. This suggests that this weed species has the potential to dominate in mixed populations.

The coefficients of variation (CV) for the individual weed species included values as low as 61, 72, and 77 % for *Silene gallica*, grasses and *Coronopus didymus* respectively. This compared with higher values of 101, 104, 122, 141 and 211 for *Chenopodium album*, *Anagallis arvensis*, *Spergula arvensis*, *Solanum nigrum* and *Cirsium* sp. respectively. The level of variability increased greatly as the mean weed seed number declined. According to Wiles *et al.*, (1992) this mean – variability relationship characterises a spatial distribution that is highly aggregated which is a common feature of weed seed banks.

5.4.2 Weed seedling emergence and species composition

Weed populations (1999/2000 growing season): In this study the DM production of both weed and crop species was monitored during the 1999/2000 growing season. The ability of the crop to suppress weeds at different plant populations was assessed by monitoring the early weed populations prior to canopy closure and by determining the weed DM at successive harvests from 60 DAS.

The weed population and DM at the end of the growing season reflected the level of crop competition by the various crops. In the no crop control plots there were higher populations and DM levels of weeds such as *Coronopus didymus*. *Anagallis arvensis* and *Trifolium repens*. This was attributed to the absence of crop competition. These weeds were reasonably well distributed across the experimental area and showed a significant density effect among treatments ($p < 0.05$).

Weed populations and weed DM production were highest in the early sown crops (September – December). However. warmer weather and high rainfall from December to February. caused late emergence of some weed species. and increased weed growth in the late sown crops. Weeds in the early sown crops emerged synchronously while weeds in late sown crops emerged unevenly. with a flush of weeds about 5 weeks after crop emergence. This is likely to be because of differences in soil preparation techniques used between the first and second sowing.

Prior to the first sowing. all plots were prepared using conventional tillage techniques. Weeds were allowed to germinate and grow in the second sowing plots and prior to crop sowing. the plots were sprayed with glyphosate. This may have contributed to the persistence of many perennial weeds. notably *Trifolium repens* and *Cirsium* sp. Reduced soil agitation in the late sown crops also meant that there would have been delayed weed emergence. Weeds would have been stimulated to grow in patches and would not be as evenly spread as weeds in the early sown plots. Fewer weeds may have also been the result of seed bank exhaustion during the 8-week interval when plots were left in fallow. Summer annuals. which were expected to germinate within 3 to 5 weeks after crop emergence. may also have been affected by the low temperatures. which also affected the initial growth of both beans and maize.

Weed DM production decreased at successive harvests in some treatments. However in most cases. weed DM production increased up to the final harvest (Chapter 3. Figure 3.2). Therefore. the shift in community dominance from weed to the crop did not occur until late in the growing season for some of the crops. Figure 5.1 shows the difference in the weed DM production in the early and late sown crops at 0.0, 0.5, 1.0, 2.0 and 4.0 x optimum populations. As indicated in Chapter 3, rape and bean plots had the highest weed DM production for the early and late sown crops, respectively.

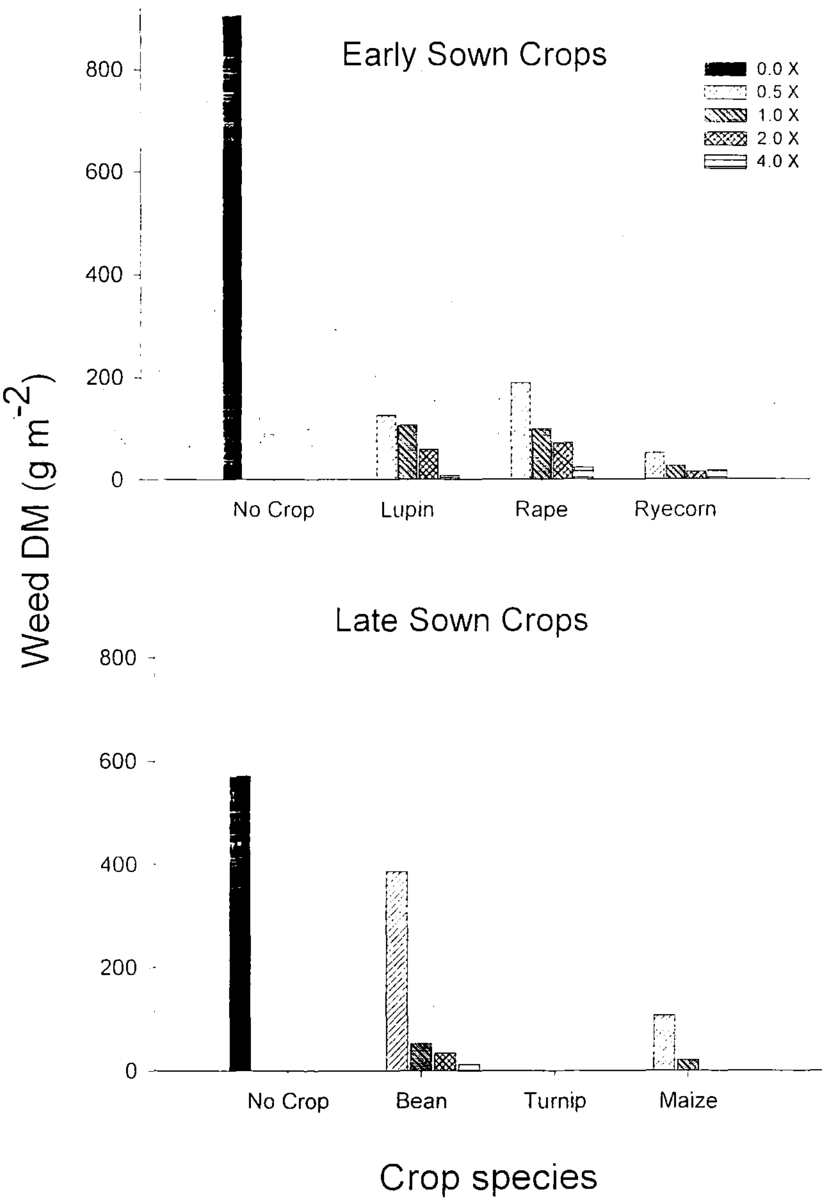

Figure 5.1. Weed DM (g/m^2) for the early and late sown crops at 0.0, 0.5, 1.0, 2.0 and 4.0 x optimum population in the 1999/2000 growing season (final harvest).

Each crop treatment behaved differently for the amount of weed DM during the trial. Bean, which had the highest weed DM at 0.5 x optimum population, jumped from 30 g/m^2 to 220 g/m^2 between the first and second harvest (52 – 80 DAS). The DM then decreased and it continued to rise and fall until the sixth harvest at 150 DAS (457 g/m^2) where maximum weed DM production was achieved. It then declined to the final harvest at 389 g/m^2 (178 DAS). At 1.0 and 2.0 x optimum population, weed DM production in bean did not show any dramatic increase. However, at 4.0 x optimum population, bean weed DM increased to 235 g/m^2 at the fourth harvest from 11 g/m^2 at the first harvest. This was probably due to high intraplant competition at this density, which caused a dramatic decrease in crop foliage at this harvest shifting the community dominance from the crop to the weed.

Unusually, this trend of increased weed DM production at the fourth and fifth harvests shifted back to the crop at the sixth to final harvest. This suggests that samples might have been taken from areas where the crop was poorly established. Alternatively, it was possibly due to patchiness of the weeds such as *Solanum nigrum* and *Chenopodium album*, which grew well above the crop canopy. A further possible explanation was that with the shedding of crop DM from crop foliage light penetrated the canopy and a niche was created for weeds to grow in this 4-week interval. However, this assumption does not explain the following decrease in weed DM production.

Community dominance, which was determined by the relative DM production at all harvests, was with the crop in all treatments. This was due to the competitiveness of these crops as combined with low weed pressure. Turnip plots produced virtually no weed DM. This was attributed to very early crop canopy closure, which decreased light penetration through the canopy, as discussed in previous chapters. This competitiveness could be attributed to the prostrate growth habit of the crop and early crop establishment.

Generally, weed DM production was lowest at high crop densities for all the crops and this was attributed to increased crop shading. Overall the number of weed species and, the DM production of the weeds decreased with increased crop density because of reduced weed growth and development.

There were a number of differences in weed species growth among the crops at varying densities. Analysis of the weed DM data on a species by species basis showed significant differences among crop treatments for *Anagallis arvensis* ($p < 0.001$), *Coronopus didymus* ($p < 0.01$), *Trifolium repens* ($p < 0.001$), *Viola* sp. ($p < 0.05$), *Polygonum aviculare* ($p < 0.001$), *Capsella bursa-pastoris* ($p < 0.001$), and grasses ($p < 0.05$).

Analysis of variance of the density effect at final harvest did not show significance for any weed species in all crops except for *Anagallis arvensis* ($p < 0.001$) in lupin. Similar studies conducted by Mohler and Liebman (1987) suggested that this pattern of no significant difference for weed species among plant densities was primarily due to the plasticity of the weeds rather than mortality. Table 3.2 and 3.3 show variability in the significant density effects for the different crops for the first to final harvests. At the first harvest, both lupin and maize density had a significant effect on weed DM ($p < 0.05$). There was a similar effect at the final harvest. Further, at the final harvest beans showed a highly significant density effect ($p < 0.001$) on weed DM production. Weed DM decreased with increased plant population.

Anagallis arvensis was the predominant weed present in the early sown crops. It increased with successive harvests at 0.0, 0.5, 1.0, and 2.0 x optimum populations. However, it was relatively constant at 4.0 x optimum population in lupin, rape and ryecorn from 52 to 160 DAS (Figure 5.2). *Anagallis arvensis* DM in competition with crops at 0.5 x optimum population was highest in lupin, followed by rape, bean, ryecorn and maize with 300, 93, 88, 55 and 16 g/m^2 at 160 DAS. In competition with other weeds in the control plots of the early sown crops this weed produced to 480 g/m^2 of DM at 160 DAS. The growth of this weed continued to increase its DM although increased plant population decreased its productivity. This result substantiates the findings of Bornkamm (1961) that increased sunlight intensity on *Anagallis arvensis* decreased its DM production. However, the relative growth of the weed increased with decreased light when grown in competition with other plants. Holms *et al.*, (1977) indicated that this weed can germinate in cool weather and it makes early spring growth. It is also able to compete at lower light intensities before other plants begin to grow. This gives this species the ability to invade open ground very early in the growing season.

There was good seedling growth of *Anagallis arvensis* at only 50 to 68 % of full sunlight. Thus, this species may be most competitive during early stages of crop growth. Crop losses can occur in this period if weed competition is severe (Holms *et al.*, 1977). However, with increased crop plant population of the different crops, suppression of this weed was sufficient to reduce the adverse competitive effects of the weed. Moreover, the ability of this weed to compete with crops such as wheat and kale (*Brassica oleracea*) is low (Welbank, 1963; Tripathi, 1968) as it is very small (Holm *et al.*, 1977). Turnip completely suppressed this weed at all densities. This was probably because turnips started to grow early in the season and reduced light interception by more than 50 %.

Trifolium repens, was the second most common weed in this trial. It was higher in the late sown crops than in the early sown crops (Figure 5.3). Bean had the highest *Trifolium repens* DM at all densities in all crops. This was followed by maize at 0.5 and 1.0 x optimum population and ryecorn at 0.5 x optimum population. This was one of the only weeds that persisted in the turnip but at extremely low quantities. At 74 DAS in turnip at 1.0 x optimum population *Trifolium repens* had a DM level of 40 g/m^2. This was probably because this harvest was taken where crop establishment was poor rather than the possibility of this weed having had the opportunity to fully establish itself.

Overall, the two Brassicas, rape and turnip and lupin suppressed *Trifolium repens* most, and the weed DM yield never exceeded 10 g/m^2. Ryecorn from the 1.0 to 4.0 x optimum population and maize at 2.0 and 4.0 x optimum population also gave *Trifolium repens* DM yields below 10 g/m^2. This demonstrated the inability of *Trifolium repens* to tolerate shade from increased crop density.

Coronopus didymus, the third most prevalent weed in this experiment, did not show any significant increase in DM accumulation at successive harvests (Figure 5.4). Maximum *Coronopus didymus* DM was produced at between 80 and 100 DAS after which the DM yields declined steadily. In the control plots *Coronopus didymus* reached its highest DM production at 80 DAS (460 g/m^2) followed by lupin, maize (at 92 DAS) and rape (112, 80, 60 g/m^2 at 0.5 x optimum population). Increasing crop plant population from 0.0 to 4.0 x optimum population significantly reduced the DM accumulation of this weed.

Figure 5.5 a, b shows the DM contribution of annuals and perennials, broadleaved and grassy weeds in the 1999/2000 growing season. Seasonal changes in weed populations indicated that all crop treatments lowered grassy and broadleaved weed population densities. Overall, broadleaved weeds consistently outnumbered grassy weeds in the 1999/2000 growing season when crops were in competition with weeds. Perennial weeds were more prevalent in the late sown crop. For example *Trifolium repens*, and *Cirsium* sp. This might be because some perennial weeds persisted despite glyphosate having been applied prior to sowing.

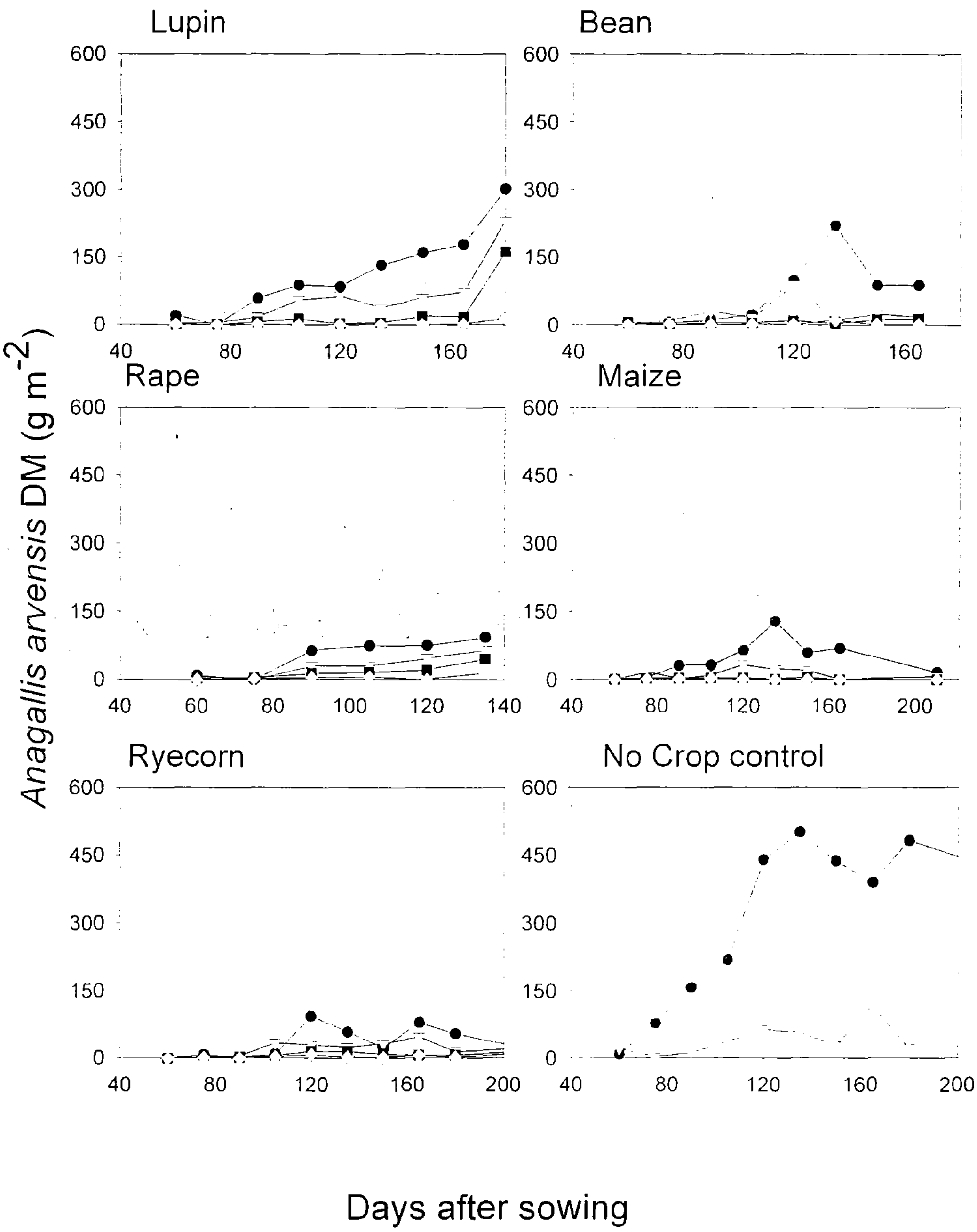

Figure 5.2. *Anagallis arvensis* DM production over time for 5 crop treatments and the no crop control at 0.5 (●), 1.0 (▽), 2.0 (■), and 4.0 (◊) x optimum population over the growing season 1999/2000. No crop control sowing 1(●) and sowing 2 (▽).

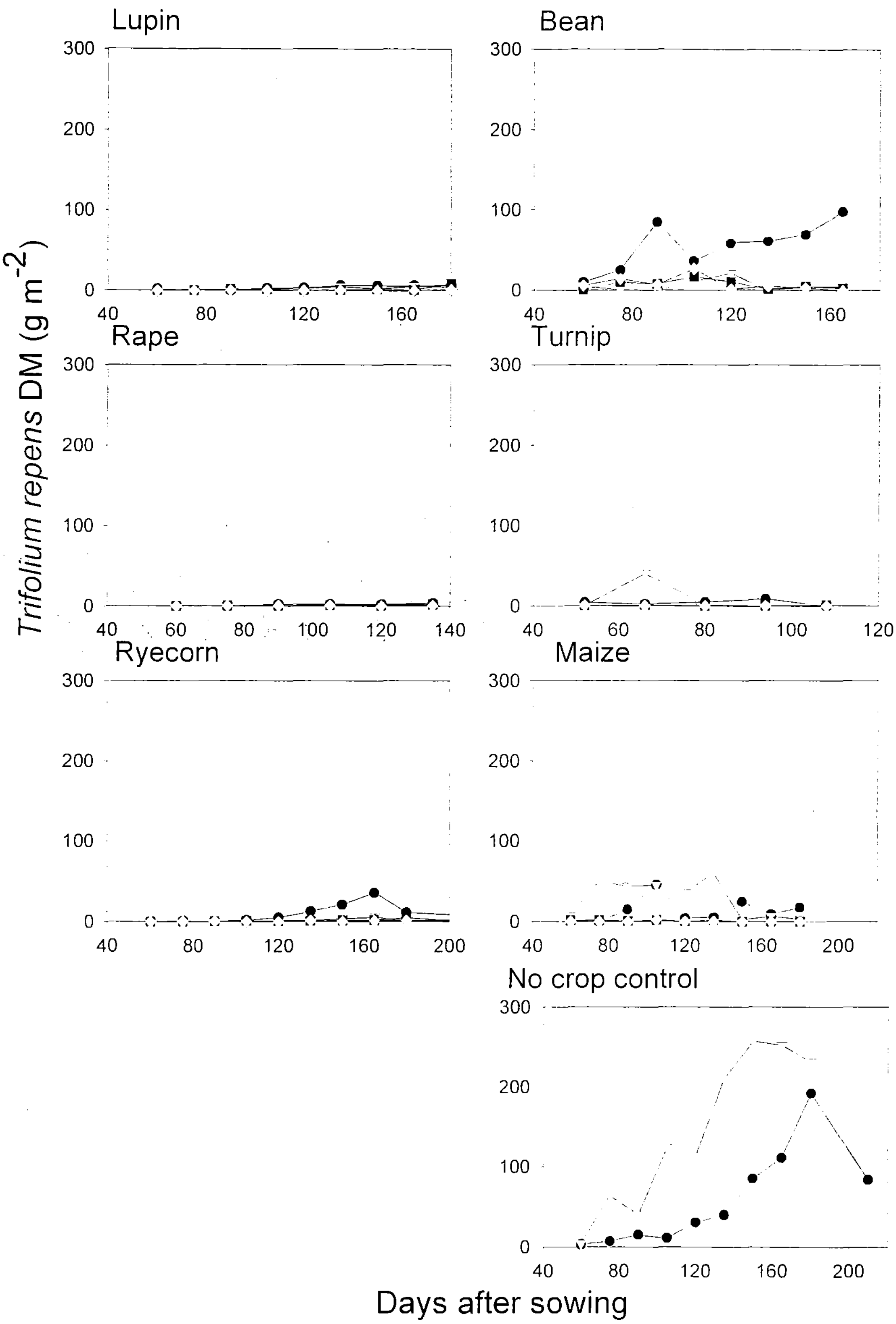

Figure 5.3. *Trifolium repens*. DM production over time for 6 crop treatments. 0.5 (●), 1.0 (▽), 2.0 (■), and 4.0 (◊) x optimum population over the growing season 1999/2000. No crop control sowing 1(●) and sowing 2 (▽).

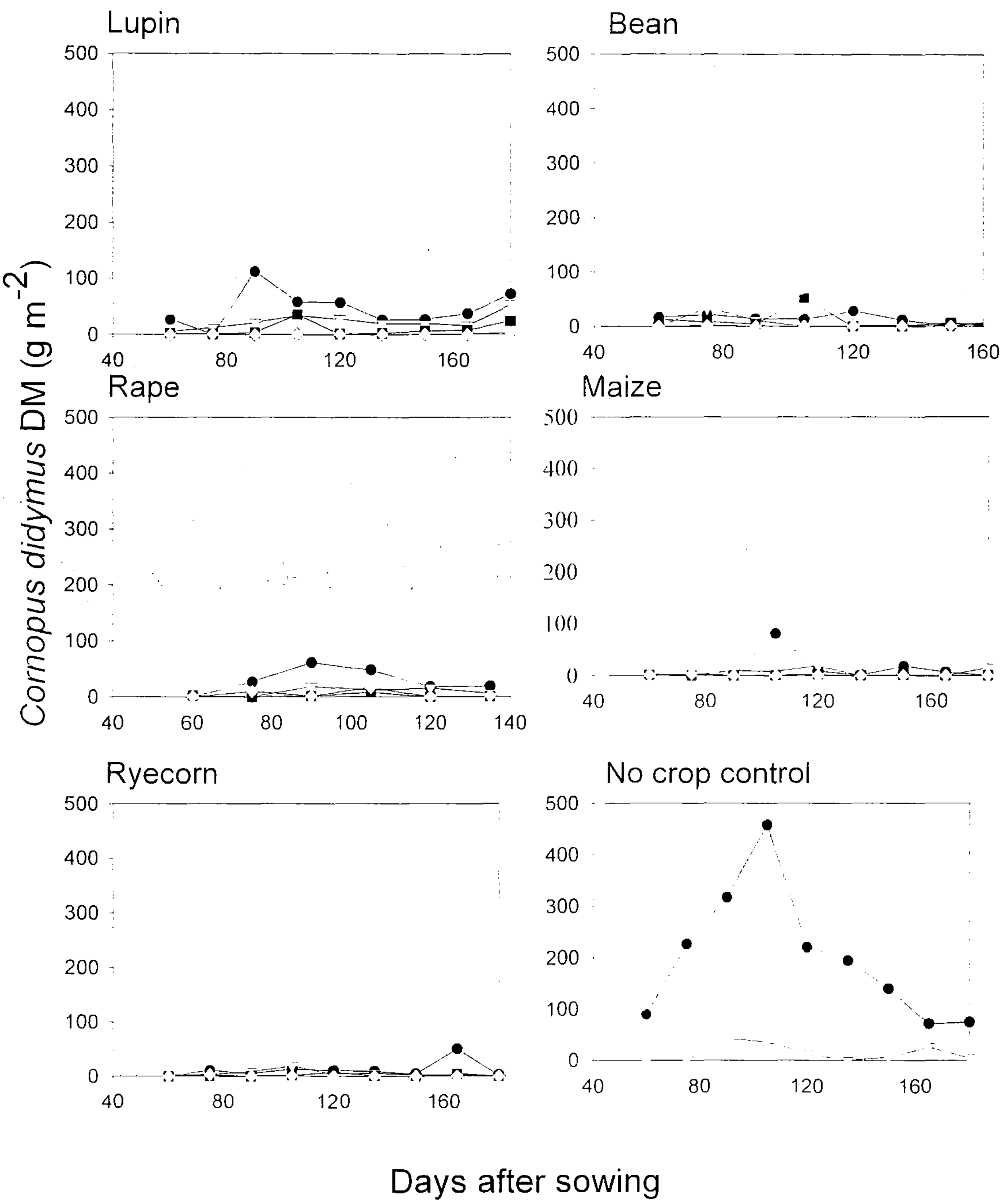

Figure 5.4. *Coronopus didymus* DM production over time for 5 crop treatments at four densities. 0.5 (●), 1.0 (▽), 2.0 (■), and 4.0 (◊) x optimum population over the growing season 1999/2000. No crop control sowing 1(●) and sowing 2 (▽).

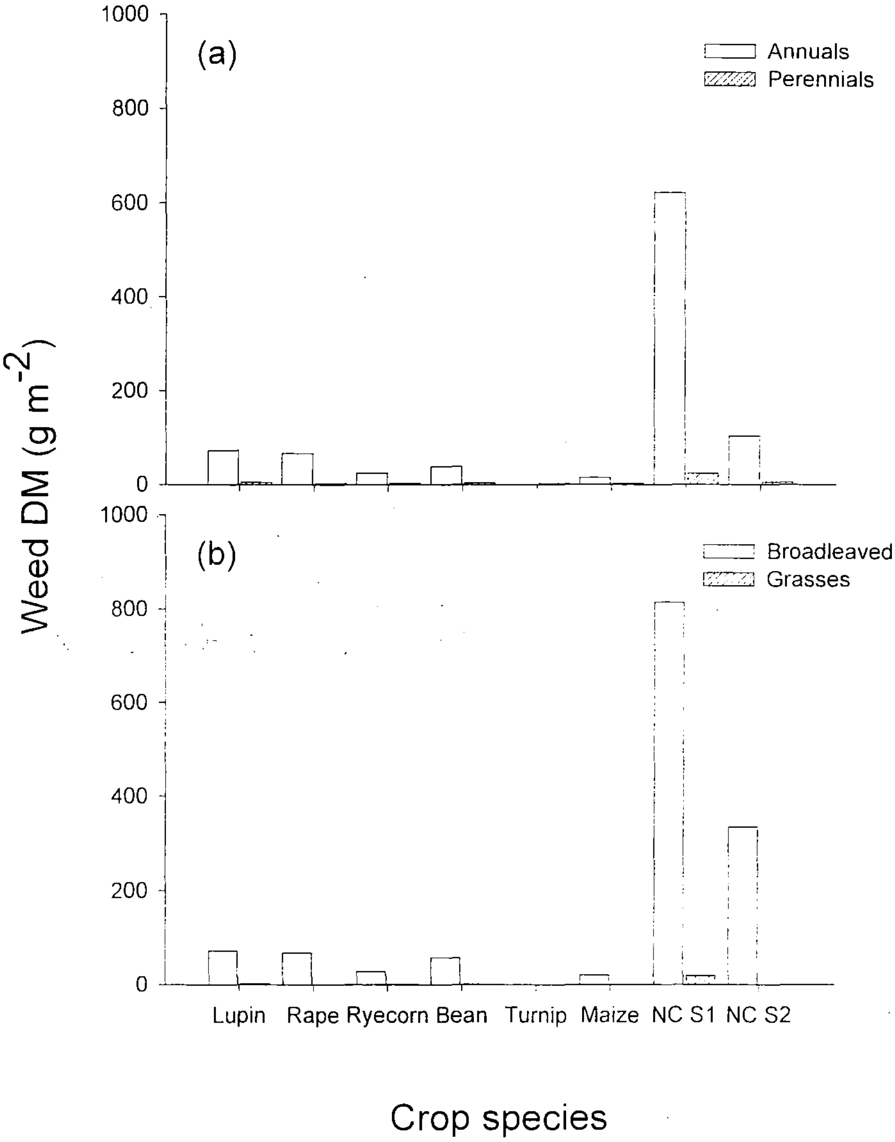

Figure 5.5. Dry matter contribution of total (a) annuals and perennials. and (b) broadleaved and grassy weeds in the 1999/2000 growing season for each crop species. NC – No crop control and S – sowing.

Bean plots produced the highest weed DM among all 6 crops and it was the least competitive crop with perennial weeds. Grass weed DM production was very low throughout the trial. However there was a both a significant crop effect ($p < 0.05$) and an interaction ($p < 0.001$). Both rape and turnip contained no grasses at all plant populations.

More than 39 weed species were recorded over the trial in the crop treatment plots and the no crop control (Table 5.4). All identifiable weed species. regardless of patchiness, were individually classified. *Coronopus didymus*, *Anagallis arvensis*, and *Trifolium repens* were the most prevalent species. A number of grasses were found throughout the trial. These included: annual poa (*Poa annua*), barley grass (*Hordeum leporium*), perennial ryegrass (*Lolium perenne*) lesser canary grass (*Phalaris minor*), vulpia hair grass (*Vulpia bromoides*), Yorkshire fog (*Holcus lanatus*), soft brome (*Bromus hordeaceus*), ripgut brome (*Bromus diandrus*) and couch (*Elytrigia repens*).

Table 5.4. Botanical and common names of all weeds recorded in the different crops, lupin, rape, ryecorn, beans, maize and turnips in the 1999/2000 growing season. Taxa identified only to generic level are shown as (sp.). Life histories shown as annual (a), biennial (b), and perennial (p).

Species	Family	Common name	Life Cycle
*Achillea millefolium**+	Asteraceae	Yarrow	p
*Carduus nutans**	Asteraceae	Nodding thistle	a or b
*Cirsium arvense**+	Asteraceae	Californian thistle	p
Cirsium vulgare	Asteraceae	Scotch thistle	b
*Crepis capillaris**+	Asteraceae	Hawksbeard	a or b
Leontodon taraxacoides+	Asteraceae	Hawkbit	p
Matricaria inodorum	Asteraceae	Scentless chamomile	a or b
*Taraxacum officinale**+	Asteraceae	Dandelion	p
*Pseudognaphalium luteo-album**	Asteraceae	Jersey cudweed	b
*Capsella bursa-pastoris**+	Brassicaceae	Shepherd's purse	a or b
*Coronopus didymus**+	Brassicaceae	Twin cress	a or b
Sisymbrium officinale	Brassicaceae	Hedge mustard	a
*Silene gallica**	Caryophyllaceae	Catchfly	a
*Spergula arvensis**+	Caryophyllaceae	Spurrey	a
*Stellaria media**+	Caryophyllaceae	Chickweed	a
*Chenopodium album**+	Chenopodiaceae	Fathen	a
Trifolium repens. *+	Fabaceae	White clover	p
Vicia sativa	Fabaceae	Vetch	a
Fumaria muralis	Fumariaceae	Scrambling fumitory	a
Erodium sp. *+	Geraniaceae	Storksbill	a or b
Poaceae sp. *+	Poaceae	Grass	a or p
Lamium amplexicaule	Lamiaceae	Henbit	a
Malva parviflora	Malvaceae	Mallow	a or b
Plantago sp. *+	Plantaginaceae	Plantain	p
*Polygonum aviculare**+	Polygonaceae	Wireweed	a
*Polygonum convolvulus**	Polygonaceae	Cornbind	a
Polygonum persicaria	Polygonaceae	Willow weed	a
Rumex acetosella +	Polygonaceae	Sheep's sorrel	p
Rumex obtusifolius +	Polygonaceae	Broad – leaved dock	p
*Anagallis arvensis**+	Primulaceae	Scarlet pimpernel	a
Aphanes arvensis +	Rosaceae	Parsley piert	a
Galium aparine	Rubiaceae	Cleavers	a
*Veronica persica**+	Scrophulariaceae	Scrambling speedwell	a
*Solanum nigrum**+	Solanaceae	Black nightshade	a
*Viola arvensis**+	Violaceae	Field pansy	a
Marrubium vulgare	Lamiaceae	Horehound	p
Total number of species	>39	Total number of a	17
Total number of families	19	Total number of b	2
		Total number of p	8
		Total number of a-b	7
		Total number of a-p	1

* Indicates weed seed species found in September 2000; + indicates weed species found in October and December 2000.

Species richness (number of weed species/treatment) was comparable to weed productivity. There were fewer weed species present in the crop treatments and most in the control plots (Table 5.5). Weed species identified increased slightly from the first to the final harvest in some crops. Weed species numbers in lupin showed the highest increase from a mean of 3 species at the first harvest (60 DAS) to 7 at the fifth harvest (120 DAS) to 12 at the final harvest (180 DAS).

Turnip was the only crop, which radically changed the weed species composition of the natural weed flora. It also had a considerable effect on suppression of weed DM production. Turnip had the lowest number of weed species present at all harvests averaging from 2 at the first harvest to 0.25 at the fifth (150 DAS) and final harvest (165 DAS). These findings are unlike those of Lawson and Topham. (1985), who found that the reduction in species number caused by the weed: crop competition was random rather than selective and decreased with time. Weed species in the control plots were relatively stable from harvest to harvest at 15 weed species for the first sowing but declined from 12 to 9 in the second sowing.

The data suggests that weed species number also declined as crop density increased in each crop. At final harvest lupin had 14 weed species at 0.5 x optimum population but there were only 9 species at 4.0 x optimum population. Similarly, rape, ryecorn, and maize showed a decrease in weed species number with increased crop density. At the fifth (150 DAS) and final (165 DAS) harvests in bean weed species number increased from 1.0 to 4.0 x optimum population. This was probably due to the increased intraplant competition at these two harvests, which gave a decline in crop DM production.

A niche was therefore opened for weed species numbers to increase. Marx and Hagedorn, (1961); McCue and Minotti, (1979); Lawson and Topham, (1985) obtained similar results with increased crop density in vining peas (*Pisum sativum*) and some other pea cultivars where weed species number declined.

Table 5.5. Weed species richness (number of weed species/treatment) for the No crop controls, lupin, rape, ryecorn, bean, turnip and maize.

Crop density	First harvest	Fifth harvest	Final harvest
No crop control			
(S_1) 0.0	15	15	15
(S_2) 0.0	12	11	9
Lupin[1]			
0.5	4	12	14
1.0	4	9	12
2.0	2	5	11
4.0	1	0	9
Rape[1]			
0.5	8	11	7
1.0	11	11	6
2.0	9	5	4
4.0	4	3	4
Ryecorn[1]			
0.5	5	13	12
1.0	5	7	7
2.0	1	9	9
4.0	0	2	5
Bean[2]			
0.5	3	13	10
1.0	9	9	9
2.0	4	9	11
4.0	1	11	12
Turnip[2]			
0.5	2	0	1
1.0	2	1	0
2.0	1	0	0
4.0	1	0	0
Maize[2]			
0.5	9	11	10
1.0	8	9	10
2.0	4	4	1
4.0	1	1	0

[1]and[2] indicate the early and late sown crops. S_1 and S_2 indicate 1st and 2nd sowing.

Table 5.6. Weed species DM g/m^2 in the 1999/2000 growing season for the early sown crops (lupin, rape, and ryecorn) at first and final harvest.

Crop density	*C. didymus*		*A. arvensis*		*Trifolium repens*		*V. arvensis*		*C. album*		*S. nigrum*		*C. bursa - pastoris*		Grasses		Total DM	
No crop control	First	Final	First	Final	First	Final	First	Final	First	Final	First	Final	First	Final	First	Final	First	Final
0.0	89.7	74.7	8.9	482.7	3.2	192.0	2.7	33.3	1.1	0.6	0.0	0.8	7.2	6.7	2.1	18.8	129.7	904.6
Lupin																		
0.5	26.3	18.0	20.5	75.3	1.7	1.5	0.0	6.6	0.0	11.3	0.0	1.3	0.0	0.0	0.0	0.6	19.0	125.0
1.0	4.5	13.4	3.2	57.7	0.1	1.0	0.0	3.4	0.0	5.4	0.0	0.0	1.9	17.0	0.0	3.5	21.7	106.4
2.0	1.9	6.0	1.1	40.3	0.0	2.1	0.0	3.7	0.0	0.6	0.0	0.8	0.0	1.1	0.0	2.1	2.3	58.8
4.0	0.0	0.7	0.0	3.5	1.0	0.2	0.0	0.8	0.0	0.2	0.0	0.0	0.0	0.3	0.0	1.1	19.9	7.3
Rape																		
0.5	0.0	20.1	8.8	92.7	0.0	3.4	0.0	0.0	0.0	9.3	0.0	1.6	3.2	0.0	0.0	0.0	51.3	189.1
1.0	0.0	7.3	7.5	64.7	0.7	3.9	0.0	0.0	0.0	3.4	0.0	0.0	0.0	0.0	0.0	0.0	41.5	98.6
2.0	2.0	0.8	2.9	44.7	0.0	1.9	0.0	0.0	0.0	0.0	0.0	1.0	1.7	0.0	0.0	0.0	11.8	72.0
4.0	0.1	1.6	0.0	14.8	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	55.7	26.2
Ryecorn																		
0.5	0.0	0.8	0.0	29.7	0.0	8.0	0.0	1.4	0.0	0.0	0.0	4.1	0.7	1.7	0.0	1.2	13.0	55.1
1.0	0.0	0.2	0.0	20.4	0.0	2.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	11.0	26.4
2.0	0.0	0.3	0.0	10.0	0.0	0.6	0.0	1.9	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.6	3.6	14.9
4.0	0.0	0.0	0.0	1.3	0.0	3.0	0.0	0.3	0.0	0.0	0.0	15.0	0.0	0.0	0.0	0.3	5.5	32.9
Significance																		
Crop x Density	***	**	***	***	NS	***	***	**	NS	-	-	NS	***	***	*	***	***	***
SEM	10.8	9.7	3.4	18.7	2.5	25.8	0.3	4.9	3.2	2.7	-	13.7	1.6	1.1	0.4	1.8	14.7	47.9
CV (%)	305.0	243.5	171.7	75.3	243.0	201.3	338.9	297.2	661.6	319.8	-	625.3	171.2	144.5	365.9	231.9	108.5	136.1

NS, non-significant; *, P < 0.5; **, P < 0.01; ***, P < 0.001. Crop density – 0.5, 1.0, 2.0, and 4.0 x optimum population. First harvest in brackets.

Table 5.7. Weed species DM g/m^2 in the 1999/2000 growing season for the late sown crops (bean, turnip and maize) at first and final harvest.

Crop density	*C. didymus*		*A. arvensis*		*Trifolium repens*		*V. arvensis*		*C. album*		*S. nigrum*		*C. bursa – pastoris*		Grasses		Total DM	
No crop control	First	Final	First	Final	First	Final	First	Final	First	Final	First	Final	First	Final	First	Final	First	Final
0.0	0.0	5.0	22.8	22.5	4.1	231.7	0.4	0.0	0.0	0.0	0.0	68.3	3.8	1.7	0.4	0.0	38.2	571.7
Bean																		
0.5	17.4	0.5	1.2	87.9	10.1	97.9	0.0	1.5	0.0	0.0	0.0	4.6	2.6	1.1	0.0	0.1	14.0	386.8
1.0	0.0	4.5	0.4	17.1	5.2	4.7	0.0	0.0	15.5	0.6	0.0	0.0	1.8	2.6	0.0	0.1	10.0	51.5
2.0	12.4	0.0	5.8	12.9	0.5	3.0	0.0	0.0	3.5	0.8	0.0	0.2	0.6	0.1	0.0	2.0	40.7	34.0
4.0	0.0	10.1	0.0	0.7	5.9	0.0	0.0	1.0	1.0	6.4	0.0	0.0	0.0	0.1	0.1	3.4	30.0	28.1
Turnip																		
0.5	0.0	0.0	0.7	0.0	4.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.7	0.0	4.0	0.1
1.0	0.0	0.0	0.2	0.0	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	2.8	0.2
2.0	0.0	0.0	1.1	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.9	0.0
4.0	0.0	0.0	1.3	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	0.0
Maize																		
0.5	0.7	0.0	0.8	15.8	0.6	17.5	0.1	18.3	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.2	13.8	106.0
1.0	2.8	15.0	0.3	7.1	0.7	3.1	0.1	1.1	0.0	0.0	0.0	0.0	12.3	0.1	0.0	0.1	8.9	28.8
2.0	0.6	0.0	0.3	0.0	1.4	0.0	0.7	0.0	0.0	0.0	0.0	0.0	3.1	0.0	0.0	0.0	4.4	0.0
4.0	0.7	0.0	0.1	0.0	0.0	0.0	0.2	0.0	0.4	0.0	0.0	15.0	0.9	0.0	0.1	0.0	19.8	0.8
Significance																		
Crop x Density	***	**	***	***	NS	***	***	**	NS	NS	-	NS	***	***	*	***	***	***
SEM	10.8	9.7	3.4	18.7	2.5	25.8	0.3	4.9	3.2	2.7	-	13.7	1.6	1.1	0.4	1.8	14.7	47.9
CV (%)	305.0	243.5	171.7	75.3	243.0	201.3	338.9	297.2	661.6	319.8	-	625.3	171.2	144.5	365.9	231.9	108.5	136.1

NS, non-significant; *, P < 0.5; **, P < 0.01; ***, P < 0.001. Crop density – 0.5, 1.0, 2.0, and 4.0 x optimum population. First harvest in brackets.

Multivariate analysis was used to further address the question of how increased plant density affected weed species composition, the different weed associations present and the contribution of each weed species to the variation (Figure 5.6). The total variation accounted for by the first two component axes of the PCA analysis was 73, 84, 91, 74, and 77 % for lupin, rape, ryecorn, bean and maize respectively. The PCA analysis therefore showed a trend between crop treatments and the composition at the weed community.

In lupin, the weed species, which accounted for the most variation included *Coronopus didymus* (Twin cress), *Chenopodium album* (Fathen), *Trifolium repens* (Clover) and *Anagallis arvensis* (Scarlet pimpernel). They were associated with the 0.5 and 1.0 x optimum populations (Figure 5.6 (a)). The higher densities (2.0 and 4.0 x optimum population) tended to cluster together. Lupin at 2.0 and 4.0 x optimum population was not associated with any weed species. This indicated that increased plant population had a significant suppression effect as previously shown. There was one discrepancy at 2.0 x optimum population, which was probably because of poor crop establishment, which resulted in increased weed species establishment in this plot.

A clear-cut density association where higher crop densities clustered together was also observed in rape (Figure 5.6 (b)). For ryecorn, bean and maize individual plots such as the 0.5 x optimum population dominated the PCA. Weeds were more strongly associated with the 0.5 x optimum population than any other density.

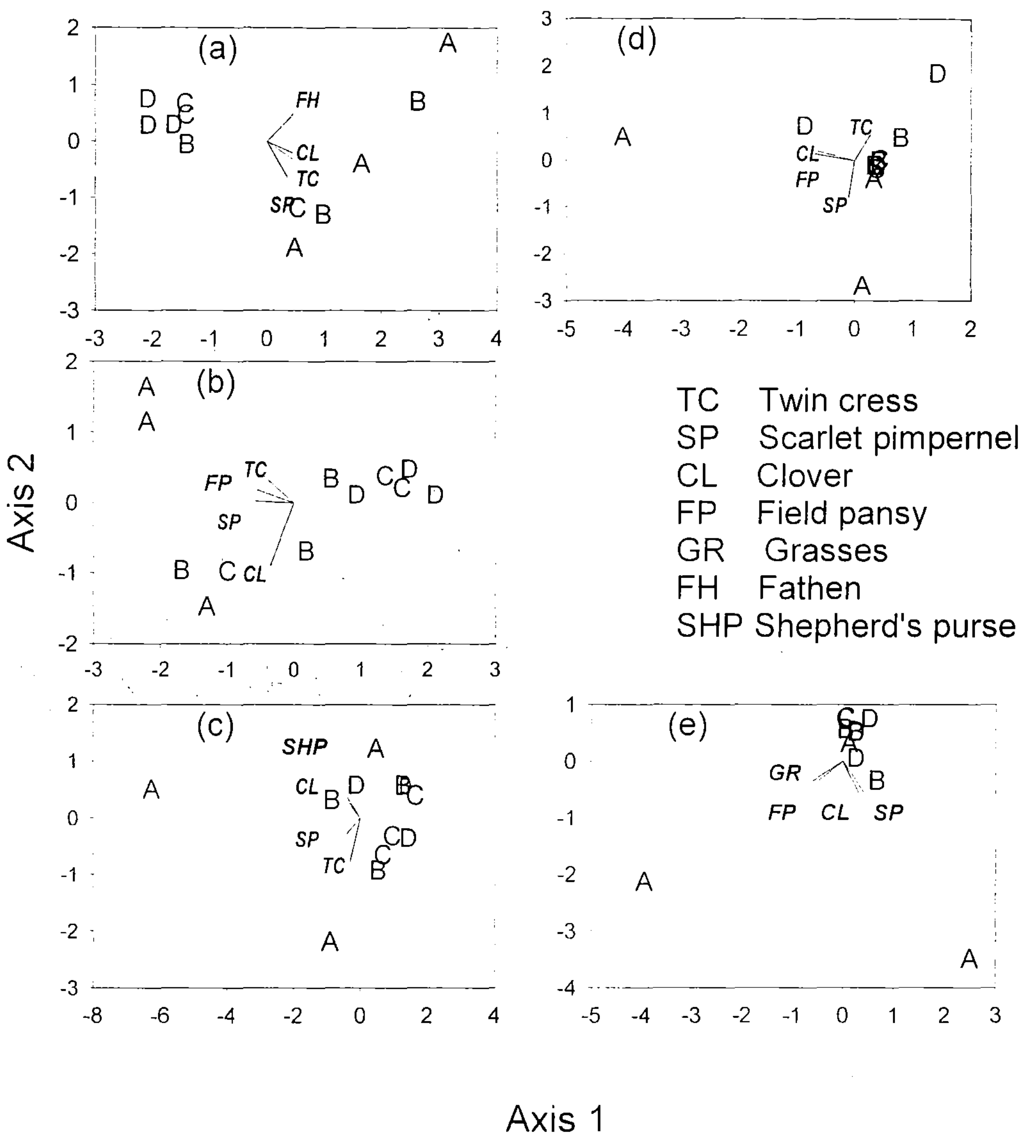

Figure 5.6. Multivariate analysis of weed species in the 1999/2000 growing season for lupin (a), rape (b), ryecorn (c), bean (d) and maize (e) treatments. A = 0.5 x optimum population, B = 1.0 x optimum population, C = 2.0 x optimum population and D = 4.0 x optimum population.

Crop canopy effects on winter weed emergence in July 2000: Over the winter when oats were sown over the entire treatment area, weed measurements were taken to ascertain the canopy effects of the 1999/2000 growing season treatments on the winter weeds as influenced by drilling oats.

There was a significant crop effect on weed community density in the oat-drilled plots ($p < 0.001$). Both rape (279.4 weeds/m^2) and bean (238.3 weeds/m^2) plots had significantly higher mean total weed numbers than the other crop treatments (Figure

5.7). Turnip (99.4 weeds/m^2) had a significantly lower weed numbers than all other crop treatments followed by maize, ryecorn, lupin, bean and finally rape.

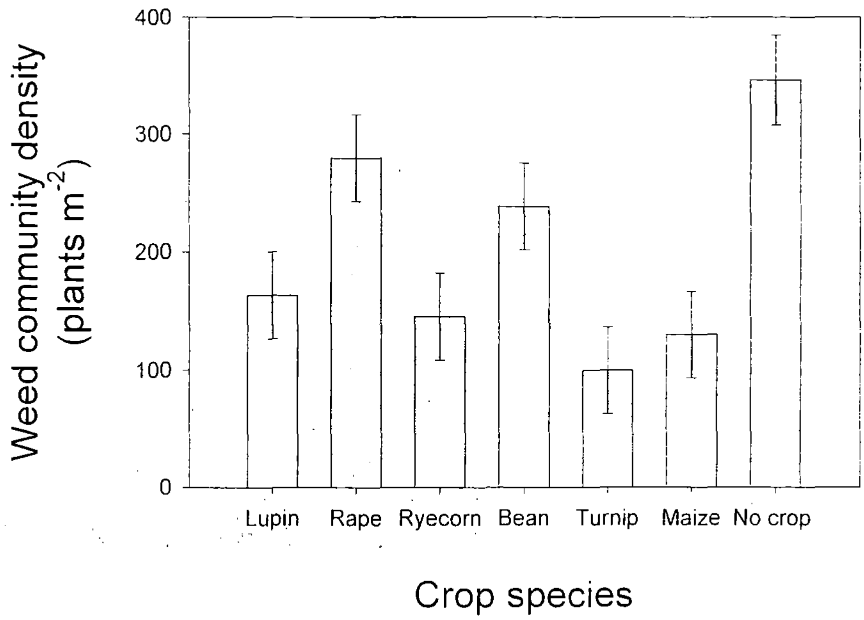

Figure 5.7. Effect of preceding crop type on the total weed plant population in winter 2000.

Increased crop plant population decreased weed numbers with significantly lower ($p < 0.05$) weed numbers at 2.0 and 4.0 x optimum population than at 0.0, 0.5 and 1.0 x optimum population (Figure 5.8). Appendix 6 and 7 shows the total number of weed plants/m^2 for the different crops in July 2000 in the early and late sown plots.

There was a significant crop x density interaction ($p < 0.001$). Weed density decreased with increased crop density in lupin, rape and maize from 221.1 – 93.3, 362.2 – 222.2 and 191.1 – 53.3 weeds/m^2 respectively from 0.5 to 4.0 x optimum population. Turnip, which had the lowest weed overall, had the highest number of weeds/m^2 at 1.0 x optimum population. This decreased to 4.0 x optimum population from 153.3 to 40.0 weeds/m^2. Early sown plots, which were previously under the no crop control, contained 114.5 more weeds/m^2 than the late sown plots.

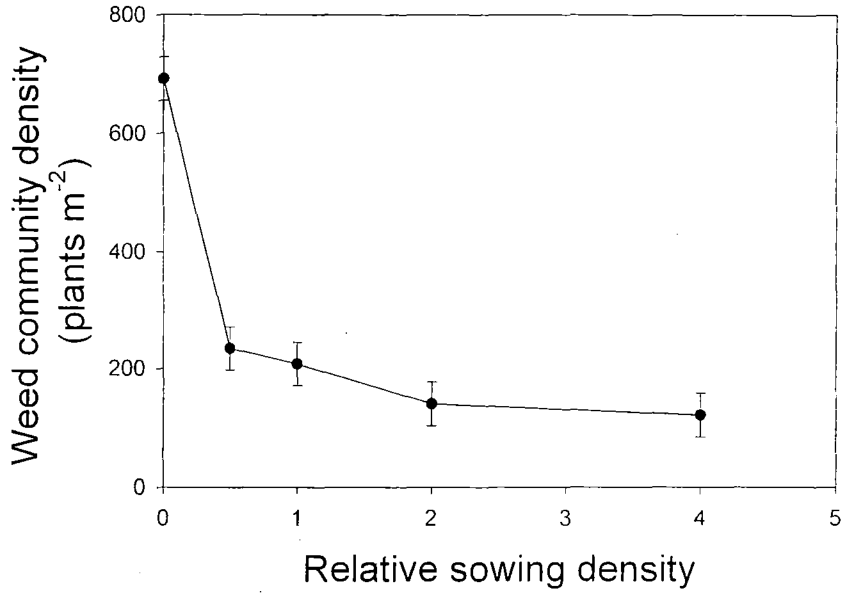

Figure 5.8. Effect of relative crop sowing density on the total weed plant population for winter weeds (2000) at 0.0, 0.5, 1.0, 2.0 and 4.0 x optimum population.

Weed species: Appendix 6 shows the 24 weed species that were identified in the July 2000 weed survey. The 8 major weed species found in the trial area were grasses (20 %), *Trifolium repens* (18 %), *Cerastium glomeratum* (14 %), *Coronopus didymus* (12 %), *Stellaria media* (10 %), *Taraxacum officinale* (9 %), *Capsella bursa-pastoris* (6 %), and *Aphanes arvensis* (4 %). Figure 5.9 shows the DM contributions of 7 of these weed species under the different previous crop treatments.

Overall, rape and bean had higher weed populations than the other crop treatments. They had high weed numbers of grasses (80 and 27 weeds /m^2 respectively), *Cerastium glomeratum* (61 and 50 weeds/m^2 respectively) and *Trifolium* spp. (40 and 41 weeds/m^2 respectively).

There was a significant crop x density interaction for grasses ($p < 0.001$), *Cerastium glomeratum* ($p < 0.05$) and *Trifolium repens* ($p < 0.001$). At the lower plant populations (0.5 and 1.0 x optimum population) weed numbers were generally higher than at 4.0 x optimum population for grasses and *Trifolium repens* in most crops.

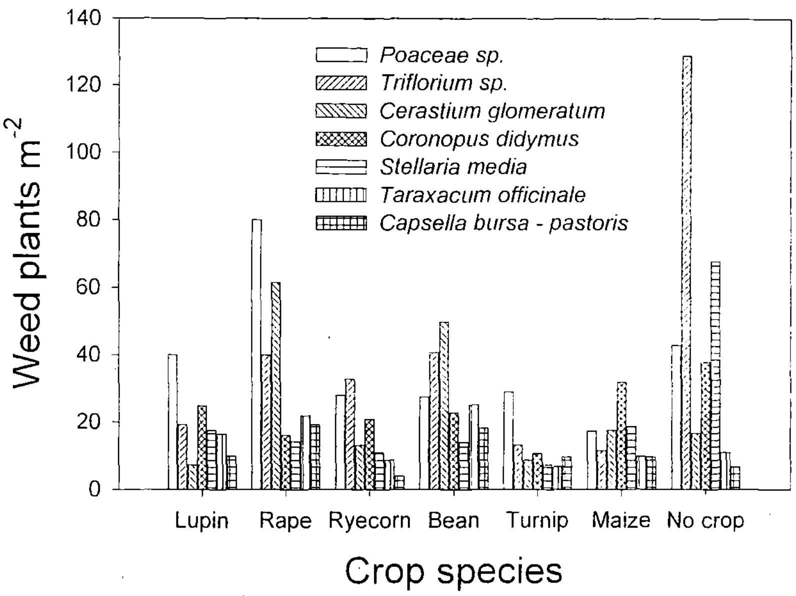

Figure 5.9. The 7 major weed species populations under the 6 crop treatments and no crop control in winter 2000.

There were more annual weeds in rape and bean plots than in any of the other crop plots ($p < 0.05$). The 0.5 and 1.0 x optimum population plots showed the highest weed numbers compared with the 2.0 and 4.0 x optimum population plots. Figure 5.10 shows average number of annual and perennial weeds present in the different crop treatments. There were significantly fewer perennials in both turnips and maize ($p < 0.05$). especially at 2.0 and 4.0 x optimum population than at 0.5 x optimum population. Perennial weed numbers were significantly less in maize plots than annual weeds at all crop densities. Over all densities only the crop gave a significant difference between annual and perennial weeds.

The density effects indicate that the 2.0 and 4.0 x optimum populations gave the most effective weed control. With increased plant population. there was a decrease in light penetration. which may have significantly reduced the weed seed germination and weed growth in these treatments.

The turnip plots continued to contain the least number of weeds at all crop densities. As explained in chapter 3. this was probably due to rapid crop establishment. which gave early canopy closure. This may have contributed to the suppression of all emerging weeds as well as contributing to reduced germination of buried weed seed because of reduced light levels penetrating the canopy. This may also reduced the dormancy of weed seed populations (McKenzie *et al.*, 1999). Additionally, the inability to set seed would have reduced weed seed inputs into the soil seed bank.

As in the 1999/2000 growing season bean and rape plots had high weed population levels. This may have been because of the canopy architecture of these crops. Following canopy closure, light levels reaching the soil were still reasonably high (> 50 %) (Chapter 3). This could have allowed germination of buried weed seeds because of the erect canopy structure of these two crops. Additionally, both crops were less competitive which may have increased weed levels very early in the season, allowing the opportunity for weeds to seed set and thus given recruitment into the soil seed bank.

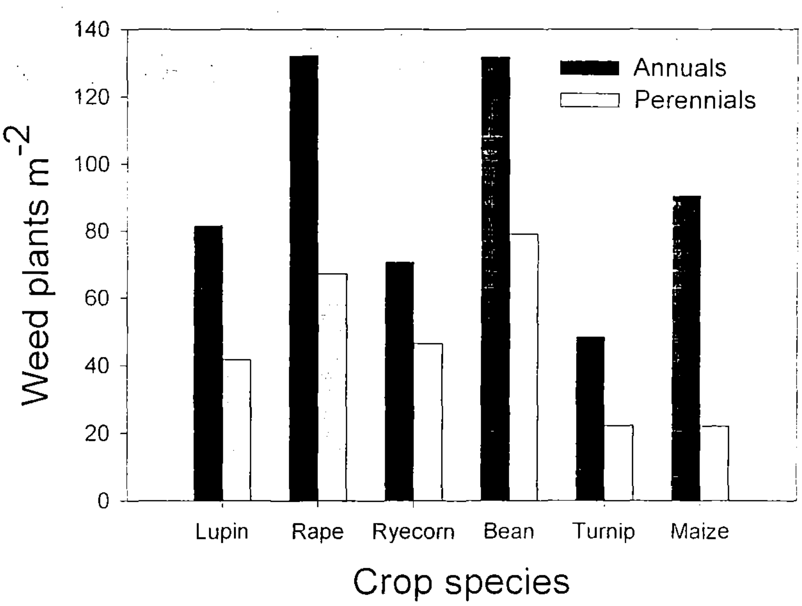

Figure 5.10. Contribution of annual and perennial weed plants in the different crop treatments.

Prior to data collection, the trial area was oversown with oats. The direct drilling of the oats may have affected the weed flora composition and population density in a number of ways. Firstly, the drilling, which is a form of minimum tillage disturbed the soil slightly. This exposed weed seeds from the buried weed seed bank and gave higher numbers of weed species in the drill rows. Secondly, the drilling may have reduced established weeds that were present in the drill rows during sowing.

The occurrence of some weed species that were either absent in 1999/2000 (*Cerastium glomeratum*) or minimally present (*Veronica persica*) may have been caused by wind carriage of seed into the experimental area. However, the presence of shelterbelts, along the northern and western sides of the experimental area should have reduced wind borne seed inputs from the strong northwest winds, which prevail in Canterbury during the summer. A single row of Douglas firs can reduce the wind speed by as much as 44 % (McKenzie *et al.*, 1999) and can affect an area 1 to 6 times the height of the tree. There may also have been some redistribution of topsoil by the wind which also could have caused seed inputs. *Veronica persica* has flat capsules, is readily wind borne, and can disperse seed over long distances (Holm *et al.*, 1997). Additionally, plants with intact capsules can be moved by the wind after senescence and spread seeds in a tumbleweed fashion (Holm *et al.*, 1997).

The relatively low occurrence of *Veronica persica* in the 1999/2000 growing season may have also been because this weed does not grow well in the shade (Holm *et al.*, 1997). Shade causes the weed seed to remain dormant in the soil. *Cerastium glomeratum* is a winter annual as is *Stellaria media*, which, accounts for their non-—occurrence in the 1999/2000 growing season. There was also no *Chenopodium album* present because the majority of germination of this weed occurs from September to November. *Capsella bursa-pastoris*, which flowers and germinates throughout the year with low germination periods in June/July and *Taraxacum officinale*, which is a rosette weed, that is green throughout the year were also present in variable amounts in the treatment plots.

Weed emergence (September 2000/2001 growing season): Weed seedling emergence showed a highly significant crop x density interaction in September of the 2000/2001 growing season ($p < 0.001$) (Table 5.8, 5.9). The average highest weed numbers were in the bean (1,163 weeds/m^2) plots. They were followed by lupin (784 weeds/m^2), ryecorn (750 weeds/m^2), rape (569 weeds/m^2), maize (313 weeds/m^2) and the lowest number of weeds was in the turnip (109 weeds/m^2) plots (Figure 5.11). As plant density increased from 0.0 to 4.0 x the optimum population weed numbers decreased (Figure 5.12). This decrease was most pronounced in lupin (1,128 – 466 seedlings/m^2), rape (1,082 – 319 seedlings/m^2) and ryecorn (1,308 – 362 seedlings/m^2) from 0.5 to 4.0 x optimum population (Table 5.8).

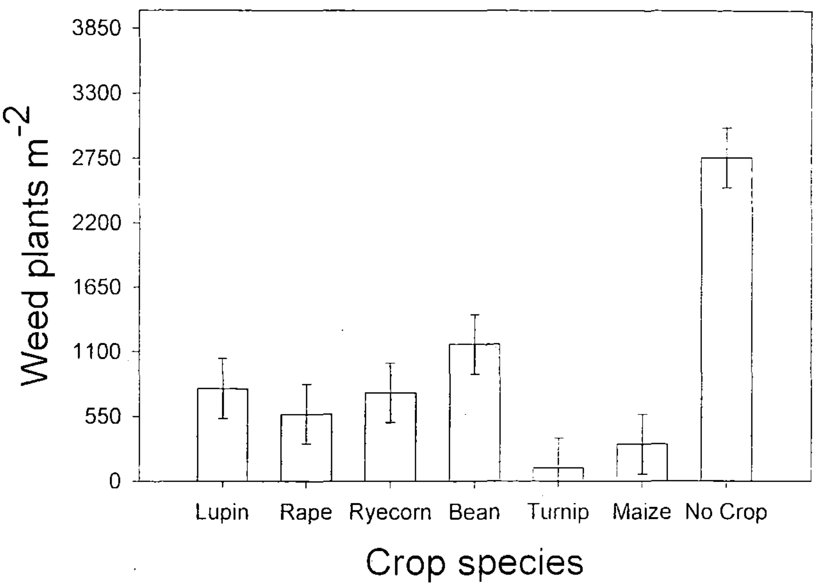

Figure 5.11. The effect of crop type on total weed population in the 2000/2001 growing season.

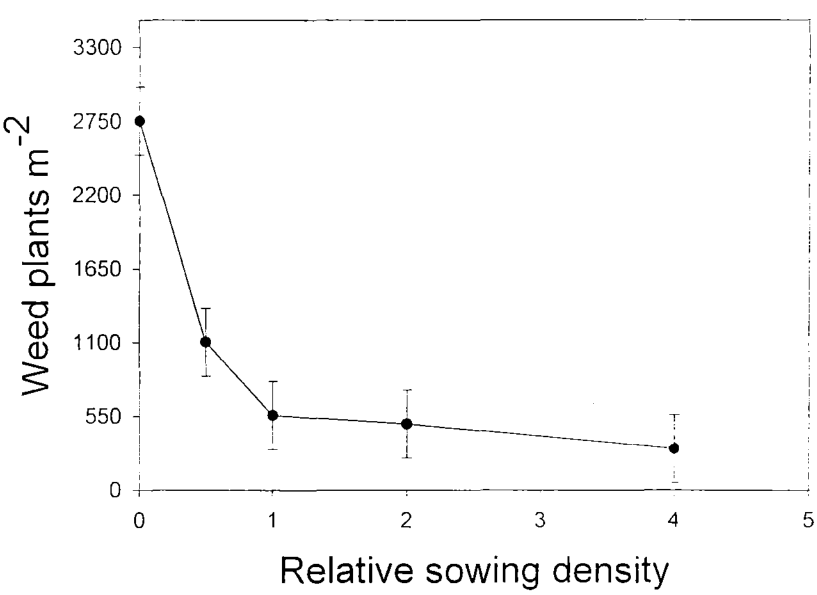

Figure 5.12. Effect of relative sowing density on the total weed population in 2000/2001 at 0.0, 0.5, 1.0, 2.0 and 4.0 x optimum population.

Over 22 weed species were identified in the 2000/2001growing season (indicated by + in Table 5.4). The 8 major weed species found in the trial were *Chenopodium album* (40 %), *Trifolium repens*, (12 %), *Anagallis arvensis* (9.5 %), *Spergula arvensis* (9 %). *Capsella bursa-pastoris* (8 %). *Viola arvensis* (6 %). *Solanum nigrum* (4 %) and *Coronopus didymus* (3 %). In *Chenopodium album* ($p < 0.001$). *Trifolium repens* ($p < 0.05$). and *Anagallis arvensis* ($p < 0.001$) there were significant crop x density interactions for the crop treatments. However. there were no observed trends with increased crop density for these weed species in the different crops.

Emergence percentage: The emergence of weed seedlings in the field as a percentage of the total seeds found by the soil extraction method (weed seeds/m^2) gave varying results. The averages of the emergence percentages are shown on Table 5.10 and 5.11. Emergence from crop treatment plots was much lower than would have been expected from the number of seeds in soil extraction samples. The average number of emerging weed seedlings ranged from 0.2 % in turnip to 1.0 % in bean plots as a percent of the total weed seed bank.

Weed emergence percentage did not appear to be affected by increased crop plant population. The highest weed emergence was at 0.5 x optimum population for ryecorn (1.0 %) and maize (0.7 %). 1.0 x optimum population for turnip (0.4 %). 2.0 x optimum population for rape (0.6 %) and 4.0 x optimum population for lupin (0.8 %).

For individual weed species emergence percentages were as high as 12.0 % in ryecorn for *Trifolium repens*. 6.4 % in rape for *Solanum nigrum*. 6.1 % in lupin for *Cirsium* sp. and 2.8 % in bean for *Chenopodium album*. *Coronopus didymus* had the lowest emergence percentages in rape. bean. turnip and maize. The highest emergence percentages in lupin was at 1.0 x optimum population for *Cirsium sp.* (21.2 %). It had the highest emergence in rape at 0.5 x optimum population at 21.0 %).

The highest emergence percentage values for *Chenopodium album* were in bean at the 2.0 x optimum population (4.8 %). These values are well within the range of percentage emergence values obtained by other researchers. Ball and Miller (1989) reported emergence percentages of 0.7. 4.0 and 25.0 % for *Chenopodium album*. redroot pigweed (*Amaranthus retroflexus*) and giant foxtail (*Setaria faberii*). respectively. Roberts and Ricketts (1979) estimated seedling number emerged to be about 5.0 % of the total weed seed bank.

Table 5.8. Weed seedling numbers/m^2 in September 2000 for early sown crop (lupin, rape and ryecorn) plots.

Crop density	*C. album*	*Trifolium repens*	*A. arvensis*	*Cirsium sp.*	*S. nigrum*	*C. didymus*	Total
No crop control							
0.0	96.0	498.0	192.0	38.0	4.0	86.0	2372.0
Lupin							
0.5	270.0	100.0	178.0	30.0	26.0	90.0	1128.0
1.0	224.0	93.0	118.5	60.5	9.5	63.5	971.0
2.0	36.0	99.0	116.5	14.5	59.5	50.0	574.0
4.0	38.0	102.0	28.0	18.5	26.0	120.0	466.0
Rape							
0.5	176.0	234.0	89.5	8.0	61.5	40.0	1082.0
1.0	28.0	50.0	202.0	0.0	26.0	14.0	510.0
2.0	49.0	43.0	24.5	4.0	94.0	12.0	366.0
4.0	22.0	47.0	49.0	2.0	35.0	12.0	319.0
Ryecorn							
0.5	91.0	300.0	286.5	18.0	48.5	34.0	1308.0
1.0	242.0	82.0	238.0	32.0	6.0	46.0	802.0
2.0	12.0	58.0	236.0	16.0	16.0	30.0	526.0
4.0	24.0	123.0	56.0	9.5	6.0	2.0	362.0
Significance							
Crop x Density	***	**	***	NS	NS	NS	***
SEM	208.4	58.5	47.1	17.3	23.3	26.7	253.9
CV (%)	108.2	87.9	91.1	162.2	98.7	140.1	46.1

NS, non-significant: *, $P < 0.5$; **, $P < 0.01$; ***, $P < 0.001$. Crop density – 0.5, 1.0, 2.0, and 4.0 x optimum population.

Table 5.9. Weed seedling numbers/m^2 in September 2000 for late sown crop (bean, turnip and maize) plots.

Crop density	*C. album*	*Trifolium repens*	*A. arvensis*	*Cirsium sp.*	*S. nigrum*	*C. didymus*	Total
No crop control							
0.0	2252.0	110.0	0.0	30.0	44.0	0.0	3135.0
Bean							
0.5	1946.0	80.0	0.0	24.0	22.0	10.0	2338.0
1.0	256.0	52.0	0.0	58.0	40.0	18.0	628.0
2.0	860.0	6.0	4.0	0.0	66.0	2.0	1236.0
4.0	56.0	96.0	0.0	10.0	40.0	8.0	451.0
Turnip							
0.5	18.0	12.0	4.0	7.0	16.0	2.0	120.0
1.0	26.0	17.0	0.0	0.0	26.0	0.0	129.0
2.0	16.0	12.0	2.0	0.0	28.0	0.0	113.0
4.0	15.0	17.0	5.0	2.0	9.0	2.0	74.0
Maize							
0.5	259.0	73.0	46.0	0.0	58.0	21.0	635.0
1.0	52.0	89.0	14.0	3.0	29.0	13.0	300.0
2.0	6.0	14.0	4.0	0.0	49.0	15.0	140.0
4.0	10.0	38.0	9.0	8.0	21.0	9.0	176.0
Significance							
Crop x Density	***	**	***	NS	NS	NS	***
SEM	208.4	58.5	47.1	17.3	23.3	26.7	253.9
CV (%)	108.2	87.9	91.1	162.2	98.7	140.1	46.1

NS, non-significant; *, $P < 0.5$; **, $P < 0.01$; ***, $P < 0.001$. Crop density – 0.5, 1.0, 2.0, and 4.0 x optimum population.

There are several possible reasons for the low weed seedling emergence percentages. Firstly, the soil was top worked with a rotary hoe and rolled to stimulate weed seedling emergence and was not fully cultivated in the 2000/2001 growing season. Roberts and Hewson (1971) suggested that on a fine, firm seedbed, twice as many seedlings might emerge than if the soil is rough. Secondly, emergence may have been severely restricted by a lack of adequate moisture from September to November when only 71 mm of rain fell. Another reason may have been because of sampling errors due to spatial variability and patchiness of some weed species or may even be due to a requirement for greater replication. It was hypothesised that turnip may have had an allelopathic influence on the weed seedling emergence in the following growing season (Grundy *et al.*, 1999). Emergence percentages indicate that emergence values were significantly lower than other percentages suggesting that allelopathy may have influenced the emergence of weed species (Table 5.11).

Roberts and Ricketts (1979) noted that the species composition of the weed flora may have more practical significance than the total number of emerged seedlings. Further, emergence percentage may not only depend on the number of seeds in the weed seed bank but also on the time of the year when the soil is disturbed. Even under optimal conditions weed species that emerge may differ to seeds found in the soil seed bank.

Coronopus didymus, which was the most abundant weed, found in the seed bank had a lower emergence percentage in all crop treatments than *Chenopodium album*. Emergence percentage in bean for *Chenopodium album* (2.8 %), which was high compared to the other crops, indicated that season had a significant effect on the emergence of this summer annual. The higher values in ryecorn (11.6 %), rape (4.7 %), maize (4.2 %), lupin (3.3 %) and bean (2.2 %) for *Trifolium repens* may have been because of lower weed seed counts which were observed for this perennial weed. The emergence percentages of all weeds in turnip were very low except for *Solanum nigrum* (3.4 %) and *Viola arvensis* (1.1 %). This was probably because of the suppressive effects of this crop during the 1999/2000 growing season. Possible reasons include allelopathy, or poor weed seed set.

Correlation of weed seed bank and seedling populations: Correlation analyses were done to describe the percentage variability in seedling density in the field attributable to the variability in the density of weed seeds in the soil seed bank (Table 5.12). Correlation coefficients ranged from -0.52 in turnips to 0.79 in rape for total weed numbers. Correlation coefficients for the no–crop control, bean, lupin, and ryecorn were not significant.

In the relationship between weed seed extraction and field emergence, correlation coefficients in rape were highest for *Chenopodium album* (0.96), *Spergula arvensis* (0.98) and *Capsella bursa-pastoris* (0.93). In ryecorn, the weed seed extraction and field emergence correlation coefficients were highest for *Capsella bursa-pastoris* (0.91), *Viola arvensis* (0.93) and *Cirsium* sp. (0.82). Lupin had a significant correlation coefficient for *Viola arvensis* (0.73) and bean for *Spergula arvensis* (0.78), turnip for *Cirsium sp.* (0.96) and maize for *Chenopodium album* (0.80). The lack of significant correlations in *Trifolium repens Anagallis arvensis*, *Solanum nigrum*, or *Coronopus didymus* suggests that seed of these species responded differently to the previous year's crop treatments.

In summary the following can be deduced from the data:

1. Rapid and complete canopy development in addition to reducing the amount of light reaching the soil surface, leading to suppressed weed growth, affected weed seed production. This had an impact on 2000/2001growing season weed populations in each crop treatment.
2. Turnip plots had the lowest weed seed numbers and bean plots, the highest.
3. Weed populations decreased as plant population increased in all crops.
4. With increased crop plant population there was a shift in species dominance away from certain weed species.
5. The results illustrate inconsistencies in the use of weed seed bank values for estimating and predicting weed seedling populations. The weed seed bank contained high numbers of *Coronopus didymus* seed in September 2000. However, *Chenopodium album* emergence was greater.
6. There was a shift in weed species dominance from *Coronopus didymus* in the 1999/2000 growing season to *Chenopodium album* in the 2000/2001 growing season.
7. Turnip effectively reduced weed resurgence and populations of all weed species.
8. Rape and bean plots at all densities contained the highest total weed DM in the 1999/2000 growing season. However, in the 2000/2001 growing season weed seed

numbers were highest in lupin followed by rape. bean. ryecorn. maize and turnip. Weed seedling numbers were highest in bean plots followed by lupin. ryecorn. rape. maize and turnip.

9. As with weed productivity. weed diversity (species richness) declined from the no–crop control to bean. followed by rape. lupin. ryecorn. maize and finally turnip. This reduction in species diversity declined further in the following order for the different plant densities: 0.0 > 0.5 > 1.0 > 2.0 > 4.0 x optimum population for all crop treatments.

10. The results confirm that correctly chosen crops and crop densities are two measures. which. can be used in integrated weed management. This can significantly affect weed development and seed production.

11. The results indicate that weeds continue to have major impacts on crop production in spite of efforts to eliminate them. Therefore. the use of some herbicide may be necessary at low plant populations (0.5 and 1.0 x optimum population) during critical period of weed – crop competition in all of the crops tested except turnip.

Table 5.10. Percent of weed seeds that emerged for 6 weed species found in the 2000/2001 growing season. (Early sown plots - lupin, rape and ryecorn).

Crop density	*C. album*	*Trifolium repens.*	*A. arvensis*	*Cirsium sp.*	*S. nigrum*	*C. didymus*	Total
No crop control							
0.0	1.21	12.50	0.10	1.33	0.35	0.02	0.27
Lupin							
0.5	2.30	5.00	0.28	2.11	1.00	0.15	0.60
1.0	0.33	3.26	0.24	21.20	1.10	0.19	0.34
2.0	0.90	1.58	0.57	1.27	3.45	0.16	0.61
4.0	0.39	11.90	0.28	0.00	1.81	0.78	0.78
Rape							
0.5	0.59	8.20	0.14	0.00	7.14	0.05	0.36
1.0	0.29	1.75	0.63	0.00	4.53	0.03	0.35
2.0	0.36	3.76	0.43	1.40	10.92	0.20	0.56
4.0	0.25	4.11	0.41	0.35	3.05	0.15	0.53
Ryecorn							
0.5	0.91	21.00	1.11	1.26	4.22	0.18	1.04
1.0	1.32	14.36	0.45	0.80	1.05	0.17	0.54
2.0	0.12	4.16	1.15	1.87	5.60	0.29	0.70
4.0	0.18	8.61	0.43	0.66	0.42	0.02	0.54

Percentage emergence:- Weed seedlings emerged / weed seed bank from the soil seed extraction method.

Table 5.11. Percent of weed seeds that emerged for 6 weed species found in the 2000/2001 growing season. (Late sown plots – bean, turnip and maize).

Crop density	*C. album*	*Trifolium repens.*	*A. arvensis*	*Cirsium sp.*	*S. nigrum*	*C. didymus*	Total
No crop control							
0.0	4.50	2.41	0.00	0.67	1.92	0.00	0.91
Bean							
0.5	2.90	1.66	0.00	2.11	0.43	0.05	0.81
1.0	3.30	3.03	0.00	0.56	0.00	0.08	0.76
2.0	4.80	1.05	0.11	0.00	5.75	0.04	1.94
4.0	0.33	3.05	0.00	1.75	4.65	0.03	0.52
Turnip							
0.5	0.15	0.70	0.05	0.08	2.78	0.09	0.21
1.0	0.28	0.85	0.00	0.00	9.06	0.00	0.35
2.0	0.22	0.83	0.03	0.00	3.25	0.00	0.21
4.0	0.13	1.00	0.35	0.23	1.57	0.02	0.10
Maize							
0.5	1.15	6.39	1.15	0.00	2.02	0.07	0.68
1.0	0.24	4.45	0.41	0.26	0.84	0.06	0.32
2.0	0.06	1.63	0.11	0.00	4.27	0.31	0.35
4.0	0.25	3.32	0.13	0.00	3.66	0.08	0.46

Percentage emergence:- Weed seedlings emerged / weed seed bank from the soil seed extraction method.

Table 5.12. Correlation coefficients for the relationship between seedling populations in 6 crops and the no crop control plots and estimates from weed seed extraction methods for 9 weed species found in the 2000/2001 growing season.

Crop Treatments	*C. album*	*Trifolium repens.*	*A. arvensis*	*S. arvensis*	*C. bursa-pastoris*	*V. arvensis*	*S. nigrum*	*C. didymus*	*Cirsium sp.*	Total
Lupin	0.43	0.07	0.68	0.34	-0.08	0.73*	-0.25	0.25	-0.27	0.67
Rape	0.96**	0.25	0.23	0.98***	0.93***	0.47	-0.20	0.47	0.66	0.79**
Ryecorn	0.61	-0.33	0.43	0.05	0.91***	0.93***	0.33	0.60	0.82**	0.67
Bean	0.40	0.14	-0.17	0.78*	0.36	-0.02	0.04	0.47	0.31	0.46
Turnip	0.28	0.17	0.35	0.21	0.08	-0.01	-0.06	0.00	0.96***	-0.52
Maize	0.80**	0.09	-0.34	0.19	0.26	0.04	0.42	0.52	-0.62	0.72*
No Crop control	-0.76	-0.42	-0.58	-0.79	-0.52	-0.92	-0.20	-0.89*	-0.33	0.54

*, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$

5.4 Conclusions

- All the crops in this trial reduced weed species composition or richness (number of weed species/treatment).
- Morphologically different crops differed in their weed species suppression.
- Increased plant population density decreased weed species composition for all crops.
- Turnip radically changed the weed species composition of the natural weed flora by suppressing the most weed species in the 1999/2000 growing season.
- Turnip weed suppression in the 1999/2000 growing season effectively lowered the weed seed bank numbers. This reduced weed resurgence and the populations of all weed species in September - December 2000.

Chapter 6

General Discussion

6.1 Overview

In a situation where the use of herbicides is being carefully scrutinised and reviewed it is becoming of greater importance that there is an understanding of how crop parameters such as species morphological characteristics and plant density may influence weed control without the need to use herbicides. The study reported here focussed on these two variables. For this purpose, 6 morphologically different crops were selected. These were forage rape (*Brassica napus* cv. Giant rape), narrow leafed lupin (*Lupinus angustifolius* cv. Fest) and ryecorn (*Secale cereale* cv. Petkusier) which were sown on 8 Septembre 1999 and maize (*Zea mays* cv. Janna), bean (*Phaseolus vulgaris* cv. Elita) and Turnip (*Brassica campestris* cv. Green globe) which were sown on 4 November 1999. These crops were further manipulated by varying their planting density from 0.5 to 4.0 x optimum population. A no–crop control was added to ascertain the effectiveness of each of these crops in the repression of weed species.

The study was conducted to test three hypotheses:

Firstly, that crop morphology can affect weed development and that increased crop density can decrease weed density. This decrease was caused by reducing the time to canopy closure. In turn this would decrease the critical period for weed control and ultimately limit or negate the need for herbicides.

Secondly, that crop and weed biomass accumulation can be modelled from the amount of light intercepted during the growing season.

Finally that, different crops may affect weed species composition differently and that fewer, smaller weeds will result with increased sowing density of a crop.

To test these hypotheses the objectives of this study focused on the:

1. Quantification of the impact of crop morphology and population density on the growth and development of the crop and its weed community.
2. Comparison of the output of a simple simulation model with independent field data on the biomass accumulation of these crops and their weeds.
3. Determination of the temporal changes in weed community species composition as affected by crop morphology and density.

6.2 Weed suppression by crops: diversity and composition of the weed community

The study showed that crop morphology could contribute considerably to weed suppression. It is perhaps, inevitable that the weed suppression ability of the different crops tested increased with their yield potential. Crops that had the highest dry matter (DM) yield very early in the growing season, such as turnip and maize had the lowest weed levels. Other crops such as lupin and rape produced high DM levels by 60 DAS, but were not as efficient in suppressing weed DM early in the growing season. Ryecorn, however, which produced the second lowest DM after bean at 60 DAS, was the second most effective crop in suppressing weeds.

The effect of crop DM on weed suppression was further influenced by increased plant population for each of the crops from 60 DAS. At 0.5 x optimum population weed yields in the crops were highest and this decreased progressively with increased plant density up to 4.0 x optimum crop population.

There was a marked difference between the control and 4.0 x optimum population in all crops. Turnip was the only crop to show no change in crop DM production at 60 DAS with change in plant population. This was because there was only a small difference in weed yield between 0.5 and 4.0 x optimum population (Figure 3.3). This was probably related to the greater inherent initial productivity of this crop, which rapidly established both DM and leaf area index (LAI) and shaded out the underlying weeds very early in the season. Weed suppression by turnip was between 95 – 99 %. Yadava and Narwal (1997) reported weed suppression of between 70 – 77 % with Indian mustard (*Brassica juncea*) which was due to early growth and development of a broad dense foliage.

Conversely rape, which showed a steady increase in DM from 0.5 to 4.0 x optimum population, showed an increase in weed DM with an unusual increase at 1.0 x optimum population at 60 DAS. Rape had a much slower initial growth than turnip. Therefore, it enabled weeds to emerge before it and this resulted in lower weed suppression.

Bean, lupin and ryecorn all showed differences between the 0.5 and 4.0 x optimum population. Lower crop plant populations intercepted less photosynthetically active radiation (PAR), and allowed more light to reach the soil surface. This created a range of fluctuating soil temperatures (Appendix 2), which promoted weed species germination and growth. Lower crop plant populations also leave open niches for the spread of weeds by propagule production and dispersal.

The results of this work clearly demonstrate differences in the sensitivity of weeds to the presence of six morphologically different crops. The work also shows that crop morphology interacts with crop density. There was some variation in the suppressive effects of certain of the crops where increased crop density had no significant effect on weed DM production as in turnip.

An important determinant of weed suppression was crop density. Bean at 0.5 x optimum population was most sensitive to weed competition at all harvests. Although bean was not as competitive as turnip, it still had a large effect on weed growth. Comparison of the weed DM production at 0.0 to 4.0 x optimum population confirms that weed production decrease as crop density increases (Rao and Shetty, 1981; Lawson and Topham, 1985).

Weed DM tended to decrease as crop productivity increased. Weed suppression by a crop such as turnip at all densities and by lupin, ryecorn, bean and maize at 2.0 and 4.0 x optimum population may provide assistance to help producers to develop improved weed management strategies that do not require the use of any herbicides.

Unfortunately, increasing crop density as a positive means of controlling weeds would not be appropriate in some grain crops. The current experiments showed reduced seed yield in response to increased plant population (Chapter 3 & Appendix 3). Holliday (1960) showed that increased plant density might reduce yield in lentils. Weed suppression was achieved at the expense of crop yield at higher crop densities. Intra-plant competition reduced grain development because of additional stress on the crops.

The canopy architecture of each of the crops also made a significant contribution to the weed suppression. Light penetrating the crop canopy influences weed germination and growth. In turnip, weed repression was due to the horizontal and flat-leaved growth habit of this species. Sunlight reaching the soil surface was reduced by more than 95 % by the turnip crop leaf canopy very early, as indicated in the days to canopy closure. This was the earliest of all 6 crops and occurred at 50 DAS. A crop canopy which, provides 95 % shade, prevents weed emergence (Urwin *et al.*, 1996). Foliar canopy alters both the amount of, and spectral quality, of light reaching the soil surface (Taylorson and Borthwick, 1968). An open crop canopy provides an opportunity for weed seeds that have no innate or induced dormancy mechanism to germinate and emerge (Urwin *et al.*, 1996). This is what happened in the no–crop control and in the 0.5 and 1.0 x optimum population plots for lupin, rape, ryecorn, bean and maize.

The characteristics that contribute to the high yield potential of a crop such as erect leaves in crops like maize and ryecorn are characteristics that may have contributed to their lack of competitiveness with weeds at 0.5 and 1.0 x optimum population. However, increased density at 2.0 and 4.0 x optimum population for these erect crops improved their competitive ability. As a result weed levels were reduced as light transmission through the canopy declined. Higher crop densities usually require less time for canopy closure than lower densities (Figure 3.17 & 3.18). Thick, erect leaves that decrease mutual shading and give high photosynthesis rates are less able to shade weeds at 0.5 and 1.0 x optimum population efficiently in ryecorn and maize.

Weed levels in the 1999/2000 growing season were low. It is possible that the results would have differed considerably had the experimental area been weedier. The low weed population probably meant that competition for light was not the only factor, which influenced crop/weed interactions.

Competition for water may also have been involved in the crop's ability to dominate the plant community. Whether water stress in weeds growing in the crop treatment plots was due to physiological characteristics of the crop or to greater DM was not determined in this experiment. However, rainfall was adequate during the growing season.

A further possible mechanism reducing weed growth may have been a residual effect due to allelopathy in the turnip plots. This was not proven conclusively despite the fact that correlation coefficients were negative between weed seed number and seedling emergence in the following, 2000/2001, growing season.

Light accounted for most of the observed weed suppression and not allelopathy per-se. Ryecorn has been reported to be allelopathic to certain weeds (Burgos and Talbert, 2000). However, there were no observed allelopathic effects between ryecorn and any of the weed species. At 2.0 and 4.0 x optimum population in all plots there was no evidence of the perennial weed *Cirsium arvense*. Generally, the crops grown in this trial were competitive. This was probably related to their large seed, which gave them a competitive growth advantage over the weeds early in the growing season (Stanton, 1984). Crops, therefore rapidly, occupied space in the community slowing weed growth, even though the weeds and the crops germinated at the same time.

As with the weed DM production, weed diversity (species richness) declined in the order control > 0.5 > 1.0 > 2.0 > 4.0 x optimum population thus validating the hypothesis that fewer weeds will occur with increased crop sowing density. It appears that some of the weed species were eliminated, possibly even before emergence, because of intense competition from the crops. In the second sowing in November, late – emerging weeds had difficulty establishing, especially in the dense growth of the turnip and high–density maize plots.

The influence of crop treatment on the composition of the weed flora parallels the effects on total weed productivity. There was a compositional gradient in the weed community, which ran from 4.0 – 2.0 – 1.0 – 0.5 – x optimum population to control (Mohler and Liebman, 1987). The 0.5 and 1.0 x optimum population flora was compositionally more similar to the no crop controls than the 2.0 and 4.0 x optimum population plots. The more dominant the crop was, the more suppressed the prominent weed species became, thus resembling the secondary weeds in their productivity (Mohler and Liebman, 1987).

With greater competition from the crop, the composition of the weed community shifted from dominant weed species such as *Coronopus didymus* or *Anagallis arvense* to a more mixed assemblage. Based on species multivariate analysis, it appears that for most crop treatments the dominant weed species were *Coronopus didymus*, *Anagalis arvensis*, *Trifolium repens* and *Viola arvensis* (Mohler and Liebman, 1987).

According to Fowler (1982) and Mohler and Liebman (1987), with dominance hierarchies, a succession of dominance among the species may have occurred. In this experiment turnip was the most competitive species, followed by maize, ryecorn, lupin, rape, bean, scarlet pimpernel and twin cress, with the other weeds falling lower in the hierarchy. The addition of a species of higher dominance class to the community such as the crop species resulted in a general suppression of less competitive weed species. The response to weed suppression by the different crop species was mainly a reduction in weed growth and development after the community canopy began to close. Planting a strongly dominant crop species not only reduces weed productivity but also shifts the relative composition of the weed community (Mohler and Liebman, 1987).

The different crop treatments in 1999/2000 significantly affected weed species composition and population dynamics. The weed seed bank maintained the predominant weed species *Coronopus didymus* from the period prior to soil cultivation in September 1999 to September 2000. The third most dominant weed species in September 1999, *Anagallis arvensis*, increased its compositional percentage in September 2000.

However, in the 2000/2001 growing season, weed emergence numbers showed a shift in the species composition dominance from a weed seed bank, which was predominantly *Coronopus didymus* to *Chenopodium album*. This weed was the dominant weed species growing despite having been only the third highest weed seed in the weed seed bank. This was more apparent in the late sown crop plots especially in the bean plots compared with the other crop plots. The numbers were least in the turnip plots.

The dominance sequence among weed species shifted from a pasture, which was predominantly in Trifolium, *repens* prior to cultivation and sowing to *Coronopus didymus* during the 1999/2000. In the 2000/2001 growing season *Chenopodium album* was dominant.

6.3 Modelling crop and weed growth

This study showed that crop and weed growth could be accurately predicted using a mechanistic model for lupin, rape and ryecorn and their weeds. The model accurately predicted substantial variations in DM accumulation for the lupin, rape and ryecorn crops at varying densities as well as weed DM accumulation.

Crop and weed growth was modelled based on light interception by the canopy. With increased crop plant population, the LAI increased. This reduced light transmitted through the canopy to the weeds below. Weed DM accumulation therefore decreased with increased crop density as reported in Chapter 3. The more rapid the canopy closure and the higher LAI of the higher plant populations (2.0 and 4.0 x optimum population) induced competition for light between weeds and the crop at an early growth stage.

The model gave insights into the reasons for variations in performance of the different crops based on their LAI and solar radiation. It did this without any input of temperature, nitrogen, water, components of yield values or any other contributory factors. Additionally, the model assumes a constant radiation use efficiency. The model, therefore, has weaknesses, based on some of the assumptions that were made. It is clear that variation in radiation use efficiency, which can occur from spectral changes in solar radiation (Sinclair and Muchow, 1999) could affect model outputs. Low fertility, and pest attacks which reduced LAI would also not be accounted for by the model and could result in inaccurate predictions.

However, the study showed that crop performance can be adequately simulated using a simple mechanistic growth model and that the mechanistic model of wheat and weed growth tested by Bourdôt *et al.*, (1999) could be used to predict growth of other crops and their weeds in Canterbury. However, the model requires further validation using a range of other crops and sowing populations.

Chapter 7

General Conclusions

7.1 Conclusions

This study has provided information on the effects of 6 morphologically different crop species on the population dynamics of a natural community of annual and perennial weed species under 4 crop densities. These results have several implications for weed management.

7.1.1 Effect of crop morphology and density on crop and weed productivity

The results indicated that varying the crop morphology and density considerably affected weed growth and development. Increasing crop plant population reduced weed production, but higher plant populations of all crops had lower yields than lower plant populations at final harvest. Turnip, at all crop densities, suppressed more than 95 % of the weed dry matter (DM) because of its ability to rapidly close the crop canopy.

7.1.2 Modelling of crop and weed growth

The results showed that crop and weed DM could be modelled mechanistically from the amount of radiation they intercept during the growing season.

7.1.3 Effect of crop morphology and density on diversity and composition of the weed community

Morphologically different crops in this trial altered weed species composition or richness. Increasing the crop plant population density altered weed species composition by producing fewer and smaller weeds. Turnip radically altered the weed species composition by reducing the species richness from 15 weeds in the no crop control to < 2 weeds. Turnip also lowered the weed seed bank by reducing weed resurgence and the populations of weed species in September - December 2000.

In summary, the crop species studied in this experiment: bean, maize, narrow leafed lupin, rape, ryecorn and turnip varied greatly in their ability to reduce weed species productivity. This was related to their morphology and the rate of early establishment of crop ground cover.

It is concluded that crop morphology and planting density could be exploited in integrated weed management programs. Turnip, regardless of crop density, has the potential to be an important crop that could be utilised in crop rotations as a smother crop. This is because of its horizontal leaf canopy, quick establishment and growth and its suppressive ability through competition for light. There is also some suggestion that it may possibly have allelopathic potential. Such competitive features have the potential for organic and conventional crop farmers to give a reduction in herbicide use in New Zealand. In addition to reduced herbicide dependence the simultaneous reduction in tillage with a consequent reduction in fossil fuel consumption would mean more environmentally benign practices that are closer to sustainability.

Reducing the population and community dominance or dominance hierarchy of the weed to the crop in the absence of herbicides could play an important role in the management of the emerging problem of herbicide resistance.

7.2 Recommendations for further research:

There is need for further research in the following areas:

- More research is needed to determine the role of soil moisture depletion and soil nutrient levels on weed suppression by high crop populations.
- Additionally, based on reports of the allelopathic potential of some crops on weed suppression, extracts containing compounds that are released under natural conditions should be tested in a bioassay to ascertain their activity.
- From a weed ecological perspective, the results of this study have emphasised the need to better understand how crop species and density influence weed populations and weed population dynamics on an individual species basis.
- Information is needed to address how differing crop species affect weed seedling recruitment, growth and subsequent seed set for individual weed species over a period of years. From this information time–growth models which include the interference of weeds with the crop for light could be developed into models that specify the effect of the crop on the population dynamics of the weed. This could eventually incorporate crop–weed competition for other resources.
- It is not clear whether the level of weed control achieved was due to crop presence or that weed pressure was very low. This indicated the need to conduct similar experiments on weedier fields or on fields, which have received minimum or no tillage prior to crop sowing.

- Varying the crop planting population from 0.0. 0.25. 0.5. 1.0. 2.0. 4.0 x optimum population would also be necessary to widen the differential crop pressure exerted on the weed flora.
- To ascertain the actual competitive effects of the crop on the weed it may be necessary to introduce a weed free control treatment for each crop density.
- Pursuing strategies to reduce weed abundance by improving crop competitive capacity may be less profitable than pursuing strategies that seek to manage the dispersal and spread of weed propagules. A better understanding of the ways that weed propagules and seeds are dispersed may lead to a more permanent solution to weed problems.
- The model developed in this work has shown its potential usefulness as an analytical tool for linking LAI to plant population increases and the competitive effects of crop species at varying densities on the dry matter accumulation of weed species. However, it needs further inputs, testing and validation to be developed into a more complex model. Changes in the quality of light as influenced by the weeds as well as the crops needs to be ascertained. Techniques therefore need to be developed to measure the leaf area of the weeds and the crops in situ.

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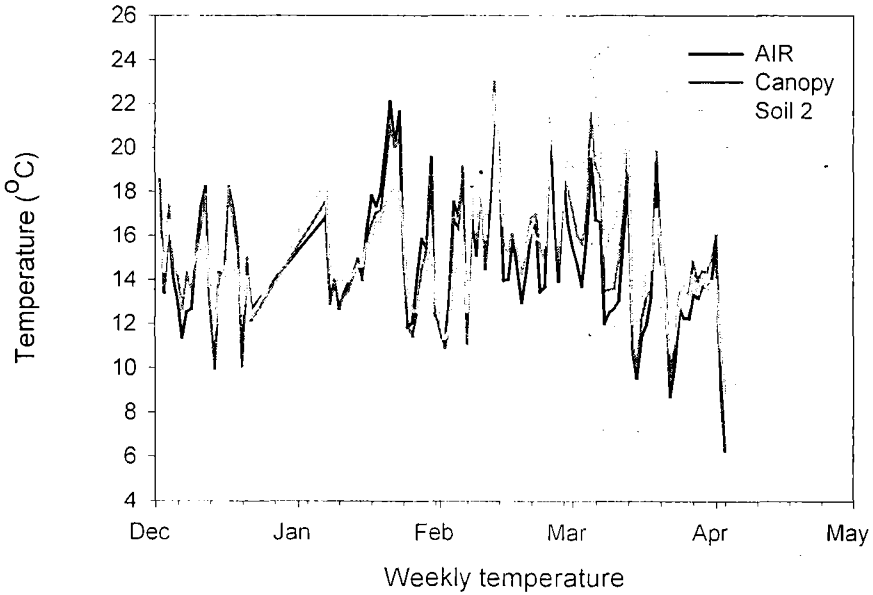
Appendix 1: Herbicide use in use in three crops grown in Canterbury 1998/99

Pesticide (FAO classification)	**Wheat** %	**Area ha:** 11,000 Loading Kg/ha/yr	**Quant** T/yr	**Green peas** %	**Area ha:** 11,000 Loading Kg/ha/yr	**Quant** T/yr	**Maize** %	**Area ha:** 11,000 Loading Kg/ha/yr	**Quant** T/yr
Phenoxy hormones	65	0.83	59.4	90	1.25	5.63			
Amides				100	0.9	4.5	100	1.5	0.75
Carbamates									
Dinitroanilines									
Urea Derivatives	80	0.40	35.2						
Sulfonylureas	20	0.20	0.33	10	0.05	0.03			
Bipyridyls				10	0.35	0.18			
Uracils									
Other hormone types (H1)	5	0.11	0.61						
Phosphonyls (H2)	10	3.00	33.6	5	1.10	0.28	10	1.10	0.06
FOPs and DIMs (H3)	30	0.22	7.3	10	0.45	0.22			
Other herbicides (H4)	16	0.64	11.2	5	2.50	0.63			
FAO Other Herbicides H1-4	61	3.97	52.1	20	4.05	1.13	10	1.10	0.06
Total Herbicides		**5.5**	**147**		**6.6**	**11.5**		**2.7**	**0.8**

Adapted from: Review of Trends in Agricultural Pesticides Use in New Zealand. MAF Policy Technical Paper 99/11. Ministry of Agriculture and Forestry (Holland and Rahman 1999)



Appendix 2. Temperature from data loggers for air, crop canopy and soil in the 1999/2000 growing season.

Appendix 3. Seeds (t/ha), harvest index (HI) and pods per plant produced in grain crops – lupin, ryecorn, bean and maize

Crop	t/ha	HI	Pods per plant
Lupin			
0.5	5.4	0.44	nd
1.0	4.2	0.36	nd
2.0	4.0	0.35	nd
4.0	3.2	0.29	nd
Ryecorn			
0.5	1.2	0.21	nd
1.0	1.2	0.21	nd
2.0	1.0	0.14	nd
4.0	1.1	0.18	nd
Bean			
0.5	1.8	0.54	16.7
1.0	2.3	0.48	10.5
2.0	2.9	0.46	8.2
4.0	2.1	0.42	4.7
Maize			
0.5	13.3	0.50	2
1.0	12.9	0.45	2
2.0	8.6	0.36	1
4.0	5.2	0.24	1
Significance			
Crop	***	***	nd
Density	***	***	nd
C x D	***	**	nd

NS, non-significant. *, $p < 0.05$. **, $p < 0.01$. ***, $p < 0.001$. Crop x density interaction CxD

Appendix 4. The simulation of ryecorn and ryecorn weed dry matter accumulation from the Excel spreadsheet at 0.5 x optimum population.

-Data on LAI and Ground Cover for model predicting crop and weed biomass progression.

-LAI=leaf area index (Destructive measurement)

-GC=ground cover (measured using digital images)

-Linear interpolation of LAI and GC to get values between sample dates

-Data on LAI and Ground Cover for model predicting crop and weed biomass progression.

-GR calculated on a daily basis. crop growth and predicted biomass

-Predicted biomass = sum of daily GR

-Units are: proportion of ground

-SR MJ m^2/day

- Biomass units are g/m^2

-N.B. Shaded areas indicate date on which actual digital images and LAI were taken.

Ryecorn DATA

		125 p/m^2				
Date	**LAI**	**GC**	**GR**	**Pred adj**	**Predicted**	**Measured**
18/09/1999		0.014231	0.186281	0.921855	0.921855	
19/09/1999		0.015654	0.306502	1.228357	1.228357	
20/09/1999		0.017077	0.326852	1.55521	1.55521	
21/09/1999		0.0185	0.270655	1.825865	1.825865	
22/09/1999		0.019923	0.37037	2.196235	2.196235	
23/09/1999		0.021346	0.464919	2.661154	2.661154	
24/09/1999		0.022769	0.500923	3.162077	3.162077	
25/09/1999		0.024192	0.340628	3.502705	3.502705	
26/09/1999		0.025615	0.583262	4.085967	4.085967	
27/09/1999		0.027038	0.56213	4.648097	4.648097	
28/09/1999		0.028462	0.663723	5.31182	5.31182	
29/09/1999		0.029885	0.739644	6.051464	6.051464	
30/09/1999		0.031308	0.736983	6.788447	6.788447	
01/10/1999		0.032731	0.741679	7.530126	7.530126	
02/10/1999		0.034154	0.860335	8.390462	8.390462	
03/10/1999		0.035577	0.794433	9.184894	9.184894	
04/10/1999		0.037	0	9.543054	9.543054	
05/10/1999		0.040286	0.221571	9.764626	9.764626	
06/10/1999		0.043571	0.172543	9.937169	9.937169	
07/10/1999		0.046857	0.340183	10.27735	10.27735	
08/10/1999		0.050143	0.584666	10.86202	10.86202	
09/10/1999		0.053429	0.869817	11.73183	11.73183	
10/10/1999		0.056714	1.079273	12.81111	12.81111	
11/10/1999		0.06	0	13.41171	13.41171	

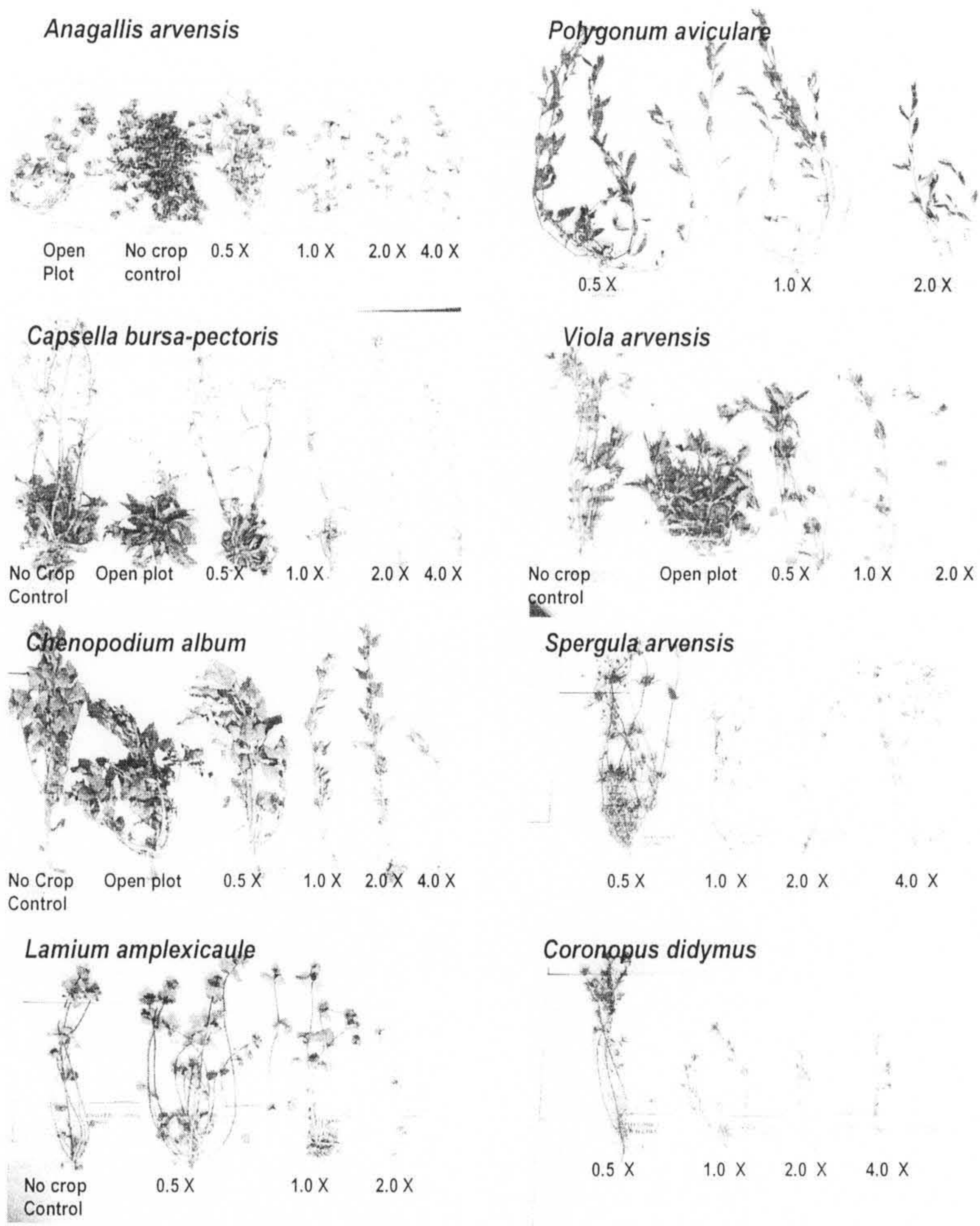
Date	LAI	GC	GR	Pred adj	Predicted	Measured
12/10/1999		0.065714	1.250543	14.66225	14.66225	
13/10/1999		0.071429	1.186429	15.84868	15.84868	
14/10/1999		0.077143	1.400143	17.24882	17.24882	
15/10/1999		0.082857	1.604114	18.85294	18.85294	
16/10/1999		0.088571	1.208114	20.06105	20.06105	
17/10/1999		0.094286	2.499514	22.56056	22.56056	
18/10/1999		0.1	0	25.39856	25.39856	
19/10/1999		0.103429	2.889794	28.28836	28.28836	
20/10/1999		0.106857	0.928589	29.21695	29.21695	
21/10/1999		0.110286	2.608257	31.8252	31.8252	
22/10/1999		0.113714	3.452366	35.27757	35.27757	
23/10/1999		0.117143	2.486943	37.76451	37.76451	
24/10/1999		0.120571	3.130034	40.89455	40.89455	
25/10/1999		0.124	0	44.04539	44.04539	
26/10/1999	0.35	0	0	47.49174	47.49174	
27/10/1999	0.428333	0.175312	2.969783	50.46152	50.46152	
28/10/1999	0.506667	0.203876	5.98783	56.44935	56.44935	
29/10/1999	0.585	0.23145	4.557256	61.00661	61.00661	
30/10/1999	0.663333	0.25807	3.520071	64.52668	64.52668	
31/10/1999	0.741667	0.283767	3.55844	71.64356	68.08512	69.6
01/11/1999	0.82	0.308575	6.652868	81.39086	74.73799	
02/11/1999	0.898333	0.332523	6.766838	88.27167	81.50483	
03/11/1999	0.976667	0.355641	11.26672	104.0383	92.77155	
04/11/1999	1.055	0.377959	6.194755	105.1611	98.96631	
05/11/1999	1.133333	0.399504	3.427748	105.8218	102.3941	
06/11/1999	1.211667	0.420303	11.46587	125.3258	113.8599	
07/11/1999	1.29	0	0	138.856	126.358	
08/11/1999	1.354286	0.456339	11.39477	149.1475	137.7527	
09/11/1999	1.418571	0.471841	15.25932	168.2714	153.012	
10/11/1999	1.482857	0.486901	6.373529	165.7591	159.3856	
11/11/1999	1.547143	0.501531	8.992454	177.3705	168.378	
12/11/1999	1.611429	0.515745	5.900118	180.1783	174.2782	
13/11/1999	1.675714	0.529553	13.22293	200.724	187.5011	
14/11/1999	1.74	0	0	224.2925	205.8968	166.53

Ryecorn weed DATA

125 p/m^2 [redacted]

	LAI	GC	GR	Pred adj	Predicted	Measured
18/09/1999		0.000136	0.001785	0.074027	0.008835	
19/09/1999		0.00015	0.002937	0.07939	0.011772	
20/09/1999		0.000164	0.003132	0.087952	0.014905	
21/09/1999		0.000177	0.002594	0.114852	0.017499	
22/09/1999		0.000191	0.00355	0.134664	0.021048	
23/09/1999		0.000205	0.004456	0.166415	0.025504	
24/09/1999		0.000218	0.004801	0.199522	0.030305	
25/09/1999		0.000232	0.003265	0.22641	0.033569	
26/09/1999		0.000245	0.00559	0.262585	0.039159	
27/09/1999		0.000259	0.005387	0.307322	0.044546	
28/09/1999		0.000273	0.006361	0.35489	0.050907	
29/09/1999		0.000286	0.007089	0.386855	0.057996	
30/09/1999		0.0003	0.007063	0.441011	0.065059	
01/10/1999		0.000314	0.007108	0.492705	0.072167	
02/10/1999		0.000327	0.008245	0.553211	0.080412	
03/10/1999		0.000341	0.007614	0.620103	0.088026	
04/10/1999		0.000355	0	0.686269	0.091459	
05/10/1999		0.000577	0.003176	0.752412	0.094635	
06/10/1999		0.0008	0.003169	0.828663	0.097804	
07/10/1999		0.001023	0.007428	0.89867	0.105232	
08/10/1999		0.001246	0.014528	0.930065	0.11976	
09/10/1999		0.001469	0.023913	0.948497	0.143673	
10/10/1999		0.001692	0.032193	0.962197	0.175866	
11/10/1999		0.001915	0	0.988097	0.19503	
12/10/1999		0.003061	0.058254	1.030956	0.253285	
13/10/1999		0.004208	0.069892	1.092556	0.323177	
14/10/1999		0.005354	0.097184	1.166618	0.42036	
15/10/1999		0.006501	0.125862	1.206658	0.546222	
16/10/1999		0.007648	0.104315	1.304527	0.650538	
17/10/1999		0.008794	0.23314	1.408933	0.883677	
18/10/1999		0.009941	0	1.543761	1.165804	
19/10/1999		0.012969	0.362355	1.709704	1.528159	
20/10/1999		0.015997	0.139014	1.842207	1.667173	
21/10/1999		0.019025	0.449942	2.13003	2.117114	
22/10/1999		0.022053	0.669529	2.47059	2.786644	
23/10/1999		0.025081	0.532469	2.921621	3.319113	
24/10/1999		0.028109	0.729709	3.097904	4.048822	
25/10/1999		0.031137	0	3.67564	4.840013	
26/10/1999	0.0385	0	0	5.902321	5.371167	
27/10/1999	0.047117	0.027416	0.464427	6.300021	5.835594	
28/10/1999	0.055733	0.032348	0.950058	7.73571	6.785652	
29/10/1999	0.06435	0.037255	0.733547	8.252747	7.519199	
30/10/1999	0.072967	0.042137	0.574746	8.668692	8.093946	
31/10/1999	0.081583	0.046994	0.589306	9.272557	8.683252	12.36

	LAI	GC	GR	Pred adj	Predicted	Measured
01/11/1999	0.0902	0.051827	1.117384	10.91802	9.800635	
02/11/1999	0.098817	0.056635	1.152519	12.10567	10.95315	
03/11/1999	0.107433	0.061419	1.94574	14.84464	12.89889	
04/11/1999	0.11605	0.066178	1.084658	15.06821	13.98355	
05/11/1999	0.124667	0.070913	0.608437	15.20043	14.59199	
06/11/1999	0.133283	0.075625	2.063043	18.71808	16.65503	
07/11/1999	0.1419	0	0	21.21355	18.93429	
08/11/1999	0.138759	0.078606	1.962792	22.85988	20.89709	
09/11/1999	0.135617	0.076897	2.486839	25.87076	23.38392	
10/11/1999	0.132476	0.075184	0.984161	25.35225	24.36808	
11/11/1999	0.129334	0.073468	1.31729	27.00267	25.68537	
12/11/1999	0.126193	0.07175	0.820816	27.32701	26.50619	
13/11/1999	0.123051	0.070028	1.748589	30.00337	28.25478	
14/11/1999	0.11991	0	0	32.88294	30.56886	52.13



Appendix 5. Differences in weed species morphology with increasing plant population for the ryecorn crop.

Appendix 6. Winter weed species numbers found in July 2000 for different crop treatments under oat. (Early sown plots)

Crop Density	*Poaceae sp.*	*Trifolium sp.*	*C. glomeratum*	*C. didymus*	*S. media*	*T. officinale*	*C. bursa – pastoris*	Total
No crop control								
0.0	63.3	142.2	14.4	53.3	87.8	20.0	0.0	403.3
Lupin								
0.5	67.8	24.4	15.5	21.1	21.1	33.3	18.9	221.1
1.0	17.8	34.5	2.2	18.9	41.1	15.6	4.4	181.1
2.0	50.0	13.4	7.8	23.3	5.6	8.9	14.4	157.8
4.0	24.1	4.4	3.3	35.6	2.2	7.8	1.1	93.3
Rape								
0.5	110.0	37.8	75.6	12.2	16.7	43.3	43.3	362.2
1.0	71.0	52.2	87.8	22.2	15.5	12.2	2.2	282.2
2.0	75.6	36.7	47.8	5.6	16.7	16.7	8.9	251.1
4.0	63.3	33.3	34.5	24.4	7.8	15.5	22.2	222.2
Ryecorn								
0.5	36.7	56.7	1.7	43.3	0.0	6.7	0.0	185.5
1.0	26.7	25.6	2.2	35.6	24.4	5.5	0.0	130.0
2.0	23.3	27.8	10.0	4.4	8.9	11.1	0.0	120.0
4.0	25.6	21.1	37.8	0.0	10.0	11.1	15.6	145.6
Significance								
Crop x Density	***	***	*	NS	*	NS	NS	***
SEM	14.5	17.8	19.9	17.9	14.0	10.1	12.5	36.8
CV (%)	67.2	101.2	135.0	138.5	137.1	117.8	188.0	33.7

NS, non-significant;*, $P < 0.5$; **, $P < 0.01$; ***, $P < 0.001$. Crop density – 0.5, 1.0, 2.0, and 4.0 x optimum population.

Appendix 7. Winter weed species numbers found in July 2000 for different crop treatments under oat. (Late sown plots)

Crop Density	*Poaceae sp.*	*Trifolium sp.*	*C. glomeratum*	*C. didymus*	*S. media*	*T. officinale*	*C. bursa – pastoris*	Total
No crop control								
0.0	22.2	115.6	18.9	22.2	47.8	23.3	13.3	288.8
Bean								
0.5	26.7	111.1	65.6	44.4	17.8	8.9	30.3	315.6
1.0	42.2	11.1	104.4	8.9	34.4	27.8	40.0	326.7
2.0	21.1	8.9	21.1	14.5	0.0	26.7	1.1	138.9
4.0	20.0	31.1	7.8	23.3	3.3	36.7	1.1	172.2
Turnip								
0.5	32.2	10.0	18.9	12.2	15.5	0.0	8.9	132.2
1.0	42.2	37.8	4.4	24.4	3.3	7.8	11.1	153.3
2.0	27.8	0.0	10.0	3.3	8.9	3.3	12.2	72.2
4.0	13.4	2.2	1.1	2.2	1.1	4.4	5.6	40.0
Maize								
0.5	42.2	12.2	27.8	15.6	38.9	16.7	20.0	191.1
1.0	23.3	30.0	14.4	50.0	22.2	12.2	8.9	174.4
2.0	2.2	3.3	26.7	32.2	4.4	10.0	6.7	100.0
4.0	1.1	0.0	1.1	30.0	4.4	0.0	2.2	53.3
Significance								
Crop x Density	***	***	*	NS	*	NS	NS	***
SEM	14.5	17.8	19.9	17.9	14.0	10.1	12.5	36.8
CV (%)	67.2	101.2	135.0	138.5	137.1	117.8	188.0	33.7

NS, non-significant;*, P < 0.5; **, P < 0.01; ***, P < 0.001. Crop density – 0.5, 1.0, 2.0, and 4.0 x optimum population.

Appendix 8. Weed species identified and their lifespan.

COMMON NAME	SCIENTIFIC NAME	ANNUAL/BIENNIAL/ PERENNIAL
Californian thistle	*Cirsium arvense*	P
Chickweed (common)	*Stellaria media*	A
Chickweed (mouse-eared)	*Cerastium glomeratum*	A
Clover (white)	*Trifolium repens*	P
Dandelion (native)	*Taraxacum officinale*	P
Docks	*Rumex obtusifolius,*	P
	Rumex crispus	
Field madder	*Sherardia arvensis*	
Field pansy	*Viola arvensis*	A
Grass (perennial)	*Lolium perenne*	P
Horehound	*Marrubium vulgare*	P
Mallows	*Malva pariflora*	A
	Malva sylvestris	P
Parsley piert	*Aphanes arvensis*	A
Scotch thistle	*Cirsium vulgare*	P
Shepherds purse	*Casella bursa-pastoris*	A
Sow-thistles	*Sonchus arvensis*	A/P
	S .asper	
	S. oleraceus	
Speedwell (scrambling)	*Veronica persica*	A
Spurrey	*Spergula arvensis*	A
Storksbill	*Erodium cicutarium*	A
Twin cress	*Coronopus didymus*	P
Yarrow	*Achillea millefolium*	P
Unspecified	-	-