DETERMINING OPTIMUM PLANT POPULATION DENSITIES FOR THREE ANNUAL GREEN MANURE CROPS UNDER WEEDY AND WEED-FREE CONDITIONS

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By
Yvonne Lawley

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ABSTRACT

Green manure crops are critical to maintaining soil fertility in organic cropping systems. However, little research has been conducted to address their contribution to weed control. Indianhead black lentil (*Lens culinaris* Medikus), AC Green Fix chickling vetch (*Lathyrus sativus* L.), and Trapper field pea (*Pisum sativum* L.) are legumes developed for use as annual green manure crops in the Northern Great Plains. Currently, no plant population density recommendations exist for these three species when grown as green manure crops under weedy conditions. The objective of this research was to determine the yield-density response of these three species under weedy and weedy-free conditions and to develop plant population density recommendations for use as annual green manure crops. Each species was grown at five plant population densities (10, 24, 64, 160, and 400 plants m^{-2}) with weedy and weed-free treatments. Wild oat (*Avena fatua* L.) and wild mustard (*Brassica kaber* (D.C.) L.C. Wheeler) were planted in weedy treatments to supplement the natural weed community. Biomass samples and soil moisture measurements were taken at early bud and full bloom to simulate when these crops would be terminated. Biomass samples from the early bud stage were analysed for total nitrogen content. Green manure biomass production for all species was lower under weedy conditions. Weed biomass in weedy treatments decreased with increasing green manure plant population density for all species. Trapper field pea was the most competitive crop while Indianhead black lentil was the least competitive. Although total plot biomass differed among species and green manure crop density, changes in soil moisture levels were not greatly affected. No significant difference in total nitrogen concentration was found among green manure species. Differences in total nitrogen accumulation occurred because of differences in biomass production. Marginal cost analysis based on green manure seed costs and their nitrogen contribution to the value of subsequent wheat crop yield were used to determine optimum plant population densities. Under weedy conditions field pea and black lentil should be planted at densities of 49-78 and 223-300 plants m^{-2}, respectively. Under weed-free conditions plant population densities for field pea and

black lentil could be reduced to 45-60 and 184-223 plants m^{-2}, respectively. No profitable plant population density was determined for chickling vetch when assuming a lower nitrogen contribution under both weedy and weed-free conditions. However, when assuming a higher nitrogen contribution, a profitable plant population density for chickling vetch of 24 plants m^{-2} was determined under weedy conditions and 32 plants m^{-2} under weed-free conditions.

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The scientific process has proven to demand intellectual, physical, and emotional endurance. Throughout this process I have been graced with timely and consistent encouragement from my husband, family, and friends. To each one, I am very grateful.

DEDICATION

This thesis is dedicated to the memory of my grandparents, Albert and Mary Van Den Bosch and Clifford and Rosa Johnson, for their pioneering spirit, their persistence in the face of adversity, their love of life, and their belief in the value of higher education.

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1.0 INTRODUCTION

Historically, green manure crops have been an important component of many cropping system strategies. There are reports of green manure crops being used by farmers in Greek, Roman, and Chinese ancient civilisations (Pieters and McKee, 1938; MacRae and Mehuys, 1985). This practice of growing plants for the purpose of incorporating their biomass back into the soil was relied upon as a means of improving soil quality and cycling nutrients before synthetic fertilizers were widely available. Settlers of the Northern Great Plains brought with them the farming practices suited to their more humid areas of origin (Army and Hide, 1959). However, early reviews of green manure crop research in North America (Pieters, 1917; Brown, 1964) report problems with green manure crops in the drier Northern Great Plains. In many situations, green manure crops were found to deplete soil water and reduce the yield of subsequent cash crops (Pieters, 1917; Brown, 1964). Clearly adaptation of green manuring practices was needed to achieve their benefits in dryland cropping systems (Army and Hide, 1959).

The introduction of synthetic fertilizers and pesticides to North American agriculture brought about a shift away from the use of green manure and forage legume crops in crop rotations and the wide spread adoption of a narrow wheat-fallow crop rotation across the Canadian Prairies (MacRae and Mehuys, 1985; Bullied et al., 2002). By the 1980's documentation of the dramatic reduction in soil organic carbon levels (Campbell and Souster, 1982) led researchers to propose a green manure strategy for the Canadian Prairies and the Northern Great Plains that was called 'green fallow.' Green fallow involved growing annual legumes during a portion of the fallow period, as a means of diversifying the wheat-fallow rotation, decreasing soil erosion, and building up soil organic matter levels (Biederbeck et al., 1993; Biederbeck et al., 1995; Brandt, 1996; Rice et al., 1993). Towards the end of the 1990's, new annual green manure species and genotypes were developed but green fallow still faced the same old limitations (Pieters, 1917). Researchers then shifted their focus towards management strategies for annual green manure crops that increase the yield of subsequent cash crops while maximizing their soil building benefits.

Despite renewed interest in green manure crops as green fallow, little research has been published to address the challenges of green manure crop management under organic conditions. Recent changes in consumer preferences have increased the demand for and profitability of organic commodities (Bullied et al., 2002). This has also resulted in a demand for research on green manure management and species selection.

Weed competition is one of the most serious challenges to organic crop production (Wallace, 2001). In the absence of chemical weed control, organic producers rely on cultural, mechanical, and biological weed management. Green manure crops can provide weed suppression through crop competition with weeds and the use of timely tillage to terminate green manure stands (Biederbeck et al., 1993; Wallace, 2001). Increasing the plant population density of green manure crops is a way to increase their ability to suppress weeds. However, there are few sources that recommend plant population densities for green manure species and no published literature supporting these recommendations. Recommended plant population densities are available for some green manure species that are also grown for seed under conventional production. These studies are based on the relationship between seeding density and seed yield rather than biomass accumulation, are primarily conducted under weed-free conditions, and assume later harvest dates than would be used for green manure crops. Thus, it is unrealistic to assume that the plant population densities developed from these studies are suitable for green manure crops under organic conditions.

In light of this informational gap, my thesis research endeavours to determine the optimal plant population densities for the following annual green manure species under weedy and weed-free conditions: black lentil (*Lens culinaris* Medikus), chickling vetch (*Lathyrus sativus* L.), and field pea (*Pisum sativum* L.). It was hypothesised that optimum plant population densities for these three species when grown as green manure crops under weedy conditions would be higher than current recommended plant population densities for seed production because of increased competition with weeds (Mohler, 2001) and their earlier termination before physiological maturity (Donald, 1963). This research also had the objectives of (1) determining the relative competitive abilities of black lentil, chickling vetch, and field pea with weeds, (2) determining if increasing green manure plant population density negatively impacted soil moisture, and (3) quantifying the relative nitrogen accumulation of black lentil, chickling vetch, and field pea as plant population density increased.

2.0 LITERATURE REVIEW

2.1 Classification of green manure crops

Green manure crops or plough down crops are grown for the purpose of incorporating their biomass into the soil, rather than for harvesting. A diverse number of terms are used to describe green manure crops, including cover crops, green fallow, and smother crops. These different names reflect the many biological functions for which green manure crops are used. Cover crops are used to protect the soil from erosion (Wallace, 2001). They may be intercropped with cash crops or grown in between cash crop seasons. Green fallow refers to annual green manure crops that are grown as a partial fallow replacement (Biederbeck et al., 1993). Smother crops are grown to suppress weed growth, while break crops are used to interrupt the life cycles of weeds and diseases (Wallace, 2001). Living mulches function both as cover and smother crops and are grown in amongst cash crops. Catch crops are grown in between cash crops to store available nutrients so that they are not lost through leaching (Wallace, 2001). This thesis will focus on green manure crops that are grown to provide the biological functions of green fallow, smother crops, and catch crops.

Green manure crops can be categorised by their ability to fix nitrogen. The majority of organic producers using green manure crops in Saskatchewan prefer to grow nitrogen fixing legume species as green manure crops (Knight and Shirtliffe, 2003). This is most likely due to their ability to enhance soil nitrogen availability.

Green manure crops may also be categorised by their plant life history. One of the most commonly grown green manure crops is yellow sweet clover (*Melilotus officianalis* L.), a biennial species that establishes itself during the first growing season and then reproduces to complete its life cycle in the second growing season. Yellow sweet clover and some perennial forages are often plowed down as a green manure crop after growing them as hay crops (Rice et al., 1993). In situations where producers are reluctant to commit their land for more than one growing season, annual green manure species or perennial species that can be grown as annuals are preferred (Bullied et al., 2002). In a 2002 survey of 46 organic farmers in Saskatchewan (Knight and Shirtliffe, 2003), 15% of producers indicated that they had grown perennial species, such as alfalfa, as green manure crops within the last five years. Thirty-five percent had grown biennial species, such as sweet clover, and 20% had grown annual species such as peas, lentil, and chickling vetch as green manure crops within the last five years.

This thesis will focus on three annual legume green manure crops that were developed for use on the Northern Great Plains and are grown for approximately 6 to 8 weeks as a partial fallow replacement during the main May to August growing season in Saskatchewan. Specifically, these three species are field pea (*Pisum sativum* L.), chickling vetch (*Lathyrus sativus* L.), and black lentil (*Lens culinaris* Medikus). The desirable characteristics of an annual legume green manure crop include: low seed cost, high nitrogen fixation, rapid growth rate, high water use efficiency, and good competitiveness with weeds (Biederbeck et al., 1993; Brandt, 1999). Annual green manure crops have been incorporated into various cropping systems as a way of increasing available soil nitrogen, reducing soil erosion, increasing soil organic matter, reducing nutrient leaching, increase microbial activity, and providing weed control (Biederbeck et al., 1993; Biederbeck et al., 1995; Brandt, 1996; Rice et al., 1993). Despite these advantages, green manure crops are not widely grown because of their indirect value, high seed costs, establishment difficulties, depletion of soil moisture reserves, or poor competition with weeds (Biederbeck et al., 1993; Biederbeck and Bouman, 1994).

2.2 Benefits of green manure crops

2.2.1 Nutrient management

It is believed that green manure crops can improve nutrient cycling within a cropping system by fixing nitrogen and by acting as short-term storage for nitrogen that might otherwise be lost through leaching, denitrification, or immobilization (Bremer and van Kessel, 1992a; Biederbeck et al., 1996). Deep rooted green manure crops, such as yellow sweet clover and alfalfa, can retrieve nitrogen and phosphorous from deep in the soil profile, increasing their availability for subsequent crops (Campbell et al., 1993; Entz et al., 2001).

Nitrogen and phosphorous are the most limiting nutrients in organic cropping systems (Knight and Shirtliffe, 2003). The majority of green manure research has focused on the nitrogen benefits of growing legumes as green manure crops (Ladd et al., 1983; Janzen et al., 1990; Rice et al., 1993; Townley-Smith et al., 1993; Zentner et al., 1996; Brandt, 1999; Bullied et al., 2002). There has been limited research focussing on the role of green manure crops to improve phosphorous cycling.

Depletion of soil organic matter limits the effectiveness of summer fallow to mineralize enough nitrogen to produce a profitable wheat crop (Biederbeck et al., 1993). Within conventional cropping systems, soil degradation could be limited by increasing cropping frequency and fertilizer use to reduce the use of summer fallow. Biederbeck et al. (1993) speculated that the effectiveness of this strategy would be limited in the Brown soil zone because of limited soil moisture and low grain prices. In organic cropping systems where the use of synthetic fertilizer sources is not permitted, the role of nitrogen fixation is even more critical to solving the problem of declining soil organic matter.

The symbiotic relationship between legume green manure crops and *Rhizobium* bacteria add nitrogen to a cropping system through nitrogen fixation. Annual legume green manures differ in their ability to fix nitrogen. Biederbeck et al. (1996) estimates average nitrogen fixation for annual green manure crops in the Brown soil zone to be 18 kg N ha^{-1} for black lentil, 49 kg N ha^{-1} for chickling vetch, and 40 kg N ha^{-1} for feed pea when using the difference method.

Townley-Smith et al. (1993) found mean nitrogen fixation by annual green manure legumes in the Dark Brown soil zone to be 15 kg N ha^{-1} for black lentil, 40 kg N ha^{-1} for field pea, 41 kg N $ha^{-1}$for faba bean, and 4 N kg ha^{-1} for annual alfalfa when measured using the acetylene reduction method. Thus field pea fixed 63% more nitrogen than black lentil. The authors believed that this low estimate for black lentil was due to poor recovery of roots which would effect estimates using acetylene reduction. Rice et al. (1993) found similar levels of apparent nitrogen fixation for black lentil in the Black soil zone, also using the acetylene reduction method. Nitrogen fixation was found to be 10 kg N ha^{-1} for black lentil, 16 kg N ha^{-1} for flat pea, and 1 N kg ha^{-1} for annual alfalfa. Rice et al. (1993) reported nitrogen fixation to vary from year to year with fluctuating climatic conditions. Caution should be used when interpreting estimates of nitrogen fixation based on the acetylene reduction assay (Gibson, 1987). This method measures nitrogenase enzyme activity, rather than absolute nitrogen fixation, and assumes a consistent relationship between acetylene reduction and nitrogen fixation (Upchurch, 1987). This conversion ratio has been found to vary from 1.5:1 to 25:1 (Upchurch, 1987).

The concentration of nitrogen in green manure crop biomass is determined by the amount of nitrogen fixation as well as plant uptake of soil nitrogen. Pikul et al. (1997) found the average nitrogen concentration of black lentil to be 2.13%. Estimation of the nitrogen concentration of black lentil by Zentner et al. (1996) was slightly higher at 2.76%. Biederbeck et al. (1996) determined the nitrogen concentration in black lentil shoots to be 2.68%. The shoot nitrogen content of chickling vetch was found to be 2.63% and that of feed pea 2.38% by Biederbeck et al. (1996). They also determined the nitrogen concentration of legume plant components. The nitrogen concentration of the nodules was several times higher than was found for any other plant part. The nitrogen concentration of legume shoots was 27% higher than found in root tissue. Among the four species examined by Biederbeck et al. (1993), feed pea produced the most biomass but had the lowest shoot nitrogen concentration. Black lentil had the least biomass production and the highest shoot nitrogen concentration. This suggests that nitrogen dilution can occur at high levels of biomass production.

The total nitrogen yield of green manure crop biomass will depend on the concentration of nitrogen in the biomass as well as the amount of biomass that can be produced. Brandt (1999) observed that the highest total nitrogen yield per unit area occurred where biomass production was maximized. Thus, plants with the capability of producing the most biomass should also accumulate the most nitrogen.

Biederbeck et al. (1996) found the total nitrogen accumulation of black lentil shoot biomass to be 40 kg ha^{-1}, while chickling vetch accumulated 49 kg ha^{-1}, and feed pea 62 kg ha^{-1}. Zentner et al. (1996) determined the nitrogen content of black lentil to be 76.2 kg ha^{-1}. Townley-Smith et al. (1993) determined average nitrogen accumulation to be 166 kg ha^{-1} for field pea, 108 kg ha^{-1} for black lentil, and 36 kg ha^{-1} for annual alfalfa. In all of these studies, pea accumulated the most nitrogen among all annual legume green manure species tested.

Upon incorporation into the soil, organic nitrogen in green manure biomass must mineralize to become plant available. This mineralization occurs over time allowing green manure nitrogen to become available gradually (Biederbeck et al., 1996). Pikul et al. (1997) found green manure treatments to have up to 66% more potentially mineralizable soil nitrogen than fallow treatments. Pikul et al. (1997) believed their results indicated that green manure crops could improve soil nitrogen reserves over the long-term. Despite higher levels of potentially mineralizable nitrogen, Pikul et al. (1997) found soil nitrate levels to be lower after green manure crops in the following spring at time of wheat planting when compared to conventionally tilled summer fallow in some years. The same was also true following chemical summer fallow, suggesting that the decomposition of plant residues was causing nitrogen immobilisation in this experiment. However, Biederbeck et al. (1996) found mean mineral soil nitrogen levels from 0 to 60 cm to be 114 kg N ha^{-1} three months following green manure incorporation, which was similar to the 122 kg N ha^{-1} following summer fallow and greater than the 69 kg N ha^{-1} following continuous wheat.

A few studies have tried to follow nitrogen movement from green manure crops to a subsequent grain crop using ^{15}N labelling. Ladd et al. (1983) monitored the movement of ^{15}N in a green manure system in Australia. They found that a wheat crop following a water medic (*Medicago littoralis* L.) annual green manure crop took up only 20 to 27% of the legume nitrogen applied. Later when comparing the uptake of nitrogen from green manure crops compared to fertilizer nitrogen, Ladd and Amato (1986) found that 17% of the applied legume nitrogen was taken up by the first subsequent wheat crop compared to 46% taken up from labeled fertilizer.

Sixty-two percent of the ^{15}N from incorporated green manure biomass remained in the soil as organic residue during the spring of the second subsequent crop. Twenty-nine percent of labeled nitrogen from the fertilizer source remained during the second subsequent crop. Total recovery of ^{15}N in crop and soil was 84 and 88% for green manure and fertilizer treatments, respectively.

In Western Canada, Janzen et al. (1990) found a wheat crop to recover an average of 14% of ^{15}N from labeled green manure biomass compared to 36% following labeled nitrogen fertilizer. On average, 53% of green manure ^{15}N remained in the soil as organic residue after the first subsequent wheat crop. Total recovery of ^{15}N in the crop and soil ranged from 19 to 83% for green manure and fertilizer treatments. In Saskatchewan, Bremer and van Kessel (1992b) found average recovery of ^{15}N in wheat "tops" was 19 and 34% for green manure and fertilizer treatments, respectively. They also found 37% of ^{15}N labeled nitrogen from annual legume green manure had mineralized in the soil by the end of the following year's growing season.

Most studies dealing with green manure crops have tried to characterize their effect by measuring changes in the yield of subsequent crops. Rice et al. (1993) found barley yields after black lentil, alfalfa, and flat pea green manure crops to be higher than those after continuous barley. Yields of barley after black lentil green manure were the highest, even when compared to summer fallow. In the first year of cropping following green manure crops, Bullied et al. (2002) reported yields and grain protein of the first subsequent wheat crop to be highest following chickling vetch and black lentil green manure crops. Wheat yields following annual alfalfa and red clover where similar or lower compared to wheat yields after fallow. In the second year of cropping following green manure crops, barley yields still remained higher following chickling vetch and black lentil compared to fallow treatments. Barley yields following alfalfa and red clover green manure crops were higher than yields following chickling vetch and black lentil in the second year. Thus, yield benefits of green manure crops have been shown to influence crop yields beyond the first subsequent crop.

Green manure crops have also been shown to increase the nitrogen content of subsequent grain crops. Biederbeck et al. (1996) found wheat grain nitrogen content to be 21 to 35% greater following annual legume green manure crops than following fertilized continuous wheat. Although the nitrogen content of the green manure crops varied significantly, green manure crop species had no influence on wheat grain nitrogen concentration. These green manure treatments resulted in a mean increase of 18 kg ha^{-1} in soil nitrogen the following spring and an increase of 5 kg ha^{-1} in the nitrogen content of a subsequent wheat crop.

Not all research has shown green manure crops to increase yields of subsequent grain crops. Brandt (1999) found the yield of wheat after a black lentil green manure crop incorporated at the early bud stage to be the same as after fallow. Pikul et al. (1997) found wheat yield, protein level, and test weight to be lower after two cycles of a green manure-wheat rotation than in a fallow-wheat rotation. Zenter et al. (1996) also found subsequent wheat yields to be lower, but nitrogen concentrations of the wheat grain were higher after green manure crop than after fallow during the last three years of the study. Yield reductions following green manure crops in these studies were believed to be due to reductions in soil moisture levels or nitrogen immobilisation as a result of green manure residue decomposition.

Despite conflicting results, researchers have reached conclusions about the effectiveness of green manure crops to improve soil nitrogen levles. Biederbeck et al. (1996) concluded that feed pea and chickling vetch green manure crops provide enough nitrogen through biological nitrogen fixation to balance nitrogen removal of a subsequent wheat crop, while black lentil could only provide 35% of the nitrogen needed. However, Pikul et al. (1997) believed that it was more realistic for green manure crops to provide only some of the nitrogen required for a subsequent grain crop, rather than all. Brandt (1996) concluded that green manure crops would be a suitable partial fallow replacement but would be uneconomical compared to growing a nitrogen fixing pea or lentil grain crop. Janzen et al. (1990) believed that the primary advantage of green manure crops was to provide long-term replenishment of stable organic nitrogen reserves.

2.2.2 Soil improvement

Many studies cite improved soil quality as a reason for growing green manure crops, but few have successfully quantified their effects. MacRay and Mehuys (1985) reviewed the literature on the effects of green manure crops on soil organic mater. Joffe (1955) stated that green manure crops were not perceived as a way to increase soil organic matter until the late nineteenth century, for they were originally grown as a source of fertilizer. By 1927, Pieters reported the most important function of green manure crops was to increase soil organic matter (Pieters, 1927). He later changed his argument to using green manure crops as a way to maintain soil organic matter (Pieters and McKee, 1938). MacRae and Mehuys were not able to draw strong conclusions about the influence of green manure crops in their literature review. They stated that "green manures maintain soil organic-matter levels under particular, though not well-defined, soil conditions, and different plant species used as green manures can vary widely in their effect" (MacRae and Mehuys, 1985, p.89). They argue that the nature of experiments performed prior to 1985 had limited their ability to draw conclusions as they only looked at a few soil parameters, not always the same ones, and that a more holistic approach must be taken to generate meaningful conclusions.

Interest in green fallow brought about new interest in determining the effects of green manure crops on soil quality during the late 1980's. The decline in soil quality, specifically soil organic matter and mineralizable nitrogen, has been documented under annual cropping systems that rely on summer fallow (Campbell and Souster, 1982). Green fallow was promoted as a way to limit the degrading effects of summer fallow and to remediate soil quality (Rice et al., 1993; Schlegel and Havlin, 1997; Biederbeck et al., 1998). Over three cycles of a green manure-wheat rotation in the Brown soil zone, Biederbeck et al. (1998) found that the more labile soil attributes of carbon and nitrogen mineralization, wet aggregate stability and light fraction organic matter were improved. Pikul et al. (1997) measured bulk density, potentially mineralizable nitrogen, total organic carbon, pH, and electrical conductivity over two cycles of a green manure–wheat rotation in Montana. After five years, only differences in potentially mineralizable nitrogen were detected in soil with green manure treatments.

Two critical factors determining soil carbon storage include the amount of organic matter entering the soil and the decomposition rate of this organic matter (Curtin et al., 2000). Biederbeck et al. (1998) found the greatest increases in soil organic carbon occurred following field pea, the green manure crop that produced the highest amount of biomass. Curtin et al. (2000) found the retention of carbon from a lentil green manure crop to be limited by its fast rate of decomposition, lower root biomass, and early incorporation into the soil. Both studies concluded that more time was needed to influence other soil quality parameters, especially total organic carbon, and that the best strategy to increase soil carbon levels was to increase the amount of green manure biomass incorporated into the soil.

A healthy soil microbial population allows for the rapid mineralization of organic nutrients, making them available for plant uptake (Hu et al., 1997; Gunapala et al., 1998). Green manure crops stimulate soil biological activity and microbial diversity in Saskatchewan. Biederbeck et al. (1995) found microbial populations and soil biochemical characteristics, including microbial biomass carbon, microbial biomass nitrogen, and soil respiration to increase in the top 10 cm of the soil profile after the third cycle of an annual legume green manure–wheat rotation. Increases in organic carbon and nitrogen were highest following feed pea green manure crops; however, microbial biomass carbon and nitrogen were highest following black lentil green manure crops. Microbial populations of bacteria, actinomycetes, filamentous fungi, yeasts, nitrifiers, and denitrifiers were higher in green manure treatments compared to summer fallow or continuous wheat.

Stimulation of soil microbial populations has also been linked to the ability of soils to provide nutrients to crops. In California, ratios of microbial carbon and nitrogen to total soil carbon and nitrogen were found to be greater in organically managed soils that regularly incorporate green manure crops compared to conventionally managed soils (Lundquist et al., 1999). The higher ratio of microbial carbon and nitrogen to total soil carbon and nitrogen suggests that soils have a greater ability to increase total carbon and nitrogen levels in the long-term

(Lundquist et al., 1999). The findings of Bremer and van Kessel (1992a) indicate that the highest levels of microbial biomass following residue incorporation occurred at the time of subsequent crop planting. This suggests that microbial biomass could prevent losses of nitrogen during periods of low crop demand and act as a nitrogen source during active crop growth (Bremer and van Kessel, 1992a).

Green fallow has also been promoted as a means to limit wind and water erosion that become problematic with frequent use of summer fallow (Campbell et al., 1990). Biederbeck et al. (1998) found that green manure rotations reduced the wind erodible fraction of the soil compared to fallow treatments. The amount of protection from wind and water erosion by annual legume green manure crops is limited by the quantity of biomass they produce and by its rate of decomposition. The amount of tillage used during incorporation will influence the rate of decomposition. Brandt (1999) cautioned that full incorporation of black lentil as a green manure did not adequately protect the soil from erosion.

2.2.3 Weed control

Green manure crops have been cited as a means of weed control, especially in organic cropping systems (Wallace, 2001). However, weed control in green manure crops has also been described as a limiting factor to the use of green manure crops (Brandt and Kirkland, 1986; Brandt, 1996). In a 2002 survey of 46 organic producers in Saskatchewan, 57% of producers incorporated green manure crops into their crop rotations (Knight and Shirtliffe, 2003). Of producers growing green manure crops, 82% indicated that they were using them to improve soil fertility and provide weed control. Only 18% reported soil fertility alone as their primary reason for growing a green manure crop, while none reported weed control alone as their primary reason (Knight and Shirtliffe, 2003). Little research has focused on the ability of green manure crops to provide weed control.

Biederbeck et al. (1993) report differences in weed biomass among green manure crop species. Feed pea had the lowest weed biomass expressed as a percent of total above ground biomass at 18%, while chickling vetch and black lentil both had 31%, and tangier flatpea had 36%. Biederbeck et al. (1998) concluded that black lentil and chickling vetch were poor weed competitors, while feed pea was relatively competitive. In a herbicide tolerance study, Wall et al. (1988) concluded that chickling vetch was a poor competitor with weeds.

Differences in weed biomass production among different green manure crop species alone does not differentiate how each species responds to weed competition. Goldberg and Landa (1991) distinguish between a species' competitive effect, the ability to suppress another plant, and its competitive response, the ability to avoid being suppressed. These effects can be quantified in terms of biomass production. Species with a relatively strong competitive effect could have a high crop biomass to weed biomass ratio as it reduces weed biomass production. A species with a relatively strong competitive response could also have a high crop biomass to weed biomass ratio as the presence of weeds does not limit its ability to produce biomass.

Jordan (1993) also describes these concepts in terms of crop suppression of weeds and crop tolerance of weeds and found that crop suppression is more desirable than crop tolerance as crop tolerance may lead to increases in weed seed bank populations and future yield losses. Ideally, a competitive green manure crop would have a strong competitive effect on weeds to reduce their biomass production and a strong competitive response to maximize its own biomass production.

Green manure crops also provide weed control for subsequent crops by facilitating the depletion of the weed seed bank. Although not studies have quantified this effect, green manure crops provide an opportunity to purge the weed seed bank without the opportunity for it to be replenished when the green manure crop is terminated before weed seed set.

2.3 Problems with green manure crops

Green manure crops are not commonly included in conventional crop rotations for many reasons. One of the primary reasons is the loss of revenue that results from setting land out of production while still incurring seed costs for a crop that is not harvested (Biederbeck et al., 1993). Other deterrents include establishment difficulties with small seeded crops, problems with weed control, and yield reductions in subsequent crops as a result of excessive water use by green manure crops (Biederbeck et al., 1993).

2.3.1 Excessive water use

Much research has focused on the effects of green manure crops on soil moisture as it has been a limiting factor in the adoption of green fallow (Biederbeck and Bouman, 1994; Zentner et al., 1996). Biederbeck et al. (1993) noted a particularly strong aversion to green fallow in the more drought-prone Brown and Dark Brown soil zones. Several authors recommend that biennial and perennial legume green manure crops are not suitable for use in the semi-arid prairies because their high water use requirements that depresses the yield of subsequent crops (Zentner et al., 1990; Biederbeck and Looman, 1985; Biederbeck et al., 1998). Annual green manure crops have also been shown to reduce yields of subsequent grain crops (Townley-Smith et al., 1993; Biederbeck and Bouman, 1994; Zentner et al., 1996; Vigil and Nielsen, 1998).

Several studies have compared soil moisture levels among green manure crops and summer fallow. In the Dark Brown soil zone, Townley-Smith et al. (1993) found average soil moisture in late September to be lower following green manure crops incorporated at the full bloom stage than following summer fallow. Average soil moisture following summer fallow was 180 mm. The average soil moisture level following a black lentil green manure was 126 mm and was not significantly different following a field pea green manure crop at 132 mm (Townley-Smith et al., 1993). The following spring significant differences remained following fallow compared to following green manure crops. The average soil moisture level following summer fallow was 175 mm. The average soil moisture level following a black lentil green manure was 142 mm and was not significantly different following a field pea green manure crop at 143 mm (Townley-Smith et al., 1993).

Biederbeck and Bouman (1994) also found soil moisture levels to be lower following both green manure treatments terminated at full bloom and continuously cropped wheat treatments than following summer fallow. Rice et al. (1993) found soil moisture levels in the spring following a black lentil green manure crop to be

3.4 mm in the 0 to 15 cm soil depth and 32.0 mm in the 15 to 120 cm soil depth. Moreover, soil moisture levels in the spring following summer fallow were not significantly different than following a green manure crop.

In the Dark Brown soil zone, Brandt (1996) found that soil moisture levels from 0 to 60 cm in the fall following black lentil green manure incorporation at the early bud stage (86 mm) were not significantly lower than after summer fallow (95 mm) when averaged over 5 years (LSD = 11). Average soil moisture levels following a grain crop of black lentil were significantly lower at 66 mm for the 0 to 60 cm soil depth (Brandt, 1996). Soil moisture levels the following spring at planting for the next crop were 110 mm following summer fallow, 107 mm following black lentil terminated at early bud, and 86 mm following grain lentil (LSD = 14).

Green manure crops vary in the absolute amount of soil moisture they use, but they also vary in the amount of biomass they can produce using the same amount of soil moisture. Biederbeck and Bouman (1994) measured the water use efficiency of four annual green manure species growing in the Brown soil zone. Black lentil was found to produce biomass at 15.1 kg ha^{-1} mm^{-1} of soil moisture used. This was similar to the water use efficiency of continuous wheat at 15.3 kg ha^{-1} mm^{-1} (based on wheat biomass). Both chickling vetch and feed pea used soil moisture more efficiently than black lentil or continuous wheat. Although not significantly different from each other, chickling vetch and feed pea produced biomass at 18.4 and 18.7 kg ha^{-1} mm^{-1}, respectively. Thus, feed pea and chickling vetch could produce more biomass than black lentil given the same amount of water as annual green manure crops.

The problem of soil moisture depletion following growing green manure crops has been observed for a long time (Pieters, 1917; Brown, 1964). However, the extensive use of fallow in dry land cropping areas has not proven to be a sustainable method to overcome soil moisture shortages (Campbell and Souster, 1982). As an alternative practice to fallow, annual legume green manure crops must also be managed carefully to avoid excessive soil moisture depletion. Green manure stand termination at the early bud stage has been shown to be critical for soil moisture conservation (Biederbeck and Bouman, 1994; Brandt, 1996; Brandt, 1999). Snow trapping, by leaving strips of standing green manure crop stubble, has shown various degrees of success as a means to increase soil moisture levels following green manure crops. Brandt (1999) found that snow trapping could increase soil moisture following green manure crops, while Townley-Smith et al. (1993) found little benefit from the practice. Management considerations also involve careful selection of green manure crops, as species such as chickling vetch and feed pea have the potential to use soil moisture more efficiently (Rice et al., 1993; Biederbeck and Bouman, 1994; Zenter et al., 1996).

2.3.2 Poor competition with weeds

Weed control in green manure crops has been identified as a major constraint to the use of green manure crops (Brandt and Kirkland, 1986; Brandt, 1996). Within conventional cropping systems, the development of herbicides has largely overcome weed problems (Brandt, 1996), but this is not the case within organic cropping systems. Poor establishment of small seeded legume green manure crops has also aggravated weed control problems with green manure crops (Biederbeck et al., 1993). Thus, larger seeded legume species may be preferred under weedy conditions. Although weed control has been identified as a problem with green manure crops, there is little research that gives data outlining the nature and extent of this problem.

2.4 Green manure management

2.4.1 Time of termination

The optimum time for green manure crop termination involves trade offs between many factors including: soil moisture levels, green manure biomass production, nitrogen fixation, and weed biomass and seed production (Biederbeck and Bouman, 1994; Smith, 2000; Wallace, 2001). Green manure termination time can be based on the number of days after planting or by the development stage of the green manure crop and weeds growing with it (Smith, 2000; Wallace, 2001). In Western Canada, annual green manure crops are often planted early in May and are terminated 8 to 10 weeks later in July or early August near the early bud or full bloom stage (eg. Biederbeck et al., 1993; Townley-Smith et al., 1993; Brandt, 1996). If termination dates are based on crop development, weather conditions can greatly influence the length of time between green manure planting and termination. Longer growing times in cool and wet years can be expected with shorter growing times in hot and dry years. In addition to the development stage of the green manure crop, the stage of weeds growing with them should be considered to minimize the return of weed seeds to the soil seed bank (Smith, 2000).

The primary dilemma for determining time of green manure crop termination is the trade-off between limiting soil moisture depletion by green manure crops and allowing enough time to maximize biomass accumulation and nitrogen fixation. Brandt (1999) found that black lentil was capable of doubling its biomass production between the early bud and full bloom stage, however this resulted in a decrease in soil moisture levels from 88 mm to 61 mm in the 0 to 90 cm soil depth when measured after harvest. Although soil moisture the following spring was higher following early bud termination at 98 mm in the 0 to 90 cm soil depth, it was not significantly different than soil moisture following full bloom termination at 87 mm. Thus, it is necessary to decide if biomass production and nitrogen fixation takes priority over moisture conservation when managing annual legume green manure cops.

2.4.2 Termination method

Green manure crops are commonly terminated and incorporated using tillage. Traditionally, the mouldboard plow was used for green manure incorporation but disk implements or heavy duty cultivators are now favoured because they leave more plant residue covering the soil surface (Smith, 2000). A two-pass system is commonly used in western Canada. The first pass is intended to terminate the plant stand and the second pass, several days later, is intended to increase plant incorporation into the soil surface (Smith, 2000). For biennial and perennial green manure crops with large amounts of biomass, cutting or mowing of the crop may be required before incorporation (Wallace, 2001).

The use of tillage to terminate green manure crops limits their compatibility with a reduced tillage cropping system. Some researchers are investigating alternative termination methods to reduce the amount of tillage used for green manure crops. Brandt (1999) compared the effect of two termination methods (tillage and herbicide) on soil moisture following green manure incorporation. Desiccation using 2,4-D amine was found to act slowly and resulted in as much water loss as experienced using a tillage operation. Bullied and Entz (1999) also compared tillage and herbicide termination methods for alfalfa (*Medicago sativa* L.). They found greater total water recharge, faster rate of water recharge, higher water use efficiency, higher levels of ground cover, and higher subsequent grain yields using herbicide termination.

Green manure termination methods have also been shown to provide weed control. Blackshaw et al. (2001) looked at the effect of termination method for yellow sweet clover green manure on weed biomass in a subsequent wheat crop. Weed biomass was found to be lower when the green manure crop was terminated using herbicides or tillage rather than when hayed or mowed.

2.4.3 Annual green manure plant population densities

There are no published studies that determine plant population density recommendations for annual green manure crops. Current plant population densities used for field pea and black lentil as green manure crops may be based on plant population densities developed for seed production of similar genotypes under weed-free conditions. Some plant population density experiments for lentil and peas take into consideration the effect of weeds (Lawson, 1982; Townley-Smith and Wright, 1994; Wall and Townley-Smith, 1996; Ball et al., 1997). However, there are no published plant population density recommendations for chickling vetch. Published experiments have used plant population densities of 50 to 55 plants m^{-2} for chickling vetch (Biederbeck et al., 1993; Bullied et al., 2002).

There are a number of recommended plant population densities for seed production of field pea in Western Canada. The Saskatchewan Pulse Production manual recommends 88 plants m^{-2} (Saskatchewan Pulse Growers, 2000), the Alberta

Pulse Production manual recommends 75 to 90 plants m^{-2} (Park and Lopetinsky, 1999), and the Canadian Organic Grower's field crop handbook recommends 60 to 80 plants m^{-2} (Wallace, 2001).

There have been suggestions to reduce the seeding rate of field pea in order to reduce seed costs, but this could increase yield losses due to inadequate weed control (Wall and Townley-Smith, 1996). Townley-Smith and Wright (1994) examined the response of field pea cultivars to plant population densities in western Canada under weedy conditions. Plant population densities tested included 6.25, 12.5, 25, 50, and 100 plants m^{-2}. Increasing plant density was able to reduce both weed numbers and weed biomass. Both Townley-Smith and Wright (1994) and Wall and Townley-Smith (1996) recommended that field peas should be seeded at 100 seeds m^{-2} in order to maximise both weed suppression and field pea yield.

There are a number of recommended plant population densities for seed production of lentil in western Canada. The Saskatchewan Pulse Production Manual recommends 130 plants m^{-2} (Saskatchewan Pulse Growers, 2000), the Alberta Pulse Production Manual recommends 108 plants m^{-2} (Park and Lopetinsky, 1999), and the Canadian Organic Grower's field crop handbook recommends 80 to 130 plants m^{-2} (Wallace, 2001). Biederbeck et al. (1993) used a target plant population density of approximately 200 plants m^{-2} as the seeding rate for black lentil as a green manure crop in a published experiment.

Ball et al. (1997) looked at the effect of plant population densities, cross seeding, and herbicides on small red lentil (*Lens culinaris* cv. crimson). They found that lentil biomass increased and weed biomass decreased with seeding rate, but this resulted in a yield increase in only one out of two years. Thus, the largest benefit to increasing lentil plant population densities was to decrease weed biomass (Ball et al., 1997). The suppressive effect of increasing lentil seeding rate on weed biomass was more pronounced when herbicides were not used. Thus, it could be expected that there are greater benefits to increasing plant population densities in organic cropping systems than in conventional cropping systems where herbicides are used.

2.5 Determining recommended plant population densities

2.5.1 Maximizing biological output

Recommendations for plant population densities may be based on the goal of maximizing biological output. The method used to determine maximum biological yield is to plant the crop at a range of densities and determine at which plant population density yield is maximized. Two general relationships between plant population density and yield have been observed. The first is an asymptotic relationship (Table 2.1 A), where yield increases with increasing plant density up to some maximum level at a higher density, after which further increases in density do not significantly change yield (Willey and Heath, 1969). This phenomenon is also known as the “law of constant final yield” (Harper, 1977). The second response is a parabolic relationship, where yield increases with increasing plant population density up to a maximum and then declines at higher densities because of greater intraspecific competition (Willey and Heath, 1969; Mohler, 2001).

Asymptotic yield-density relationships are more characteristic of crop biomass production (Mohler, 2001). Parabolic yield-density relationships (Table 2.1 B) are more typical of seed yields for crop plants (Mohler, 2001). The apex of the parabolic curve may be wider for plants with a greater number of smaller reproductive units (eg. wheat and canola) and more rounded for crops with fewer but larger reproductive units (eg. corn and sunflower) because of greater sensitivity to intraspecific competition (Mohler, 2001). Crops having a parabolic yield-density relationship with a wider apex (Table 2.1 C) for seed yield may appear to have an asymptotic yield-density relationship if high enough densities are not included in the experiment’s treatment design.

It has been debated if maximum aboveground plant biomass production occurs at the same plant population density as maximum seed yield. Harper (1977) stated that the optimal density for maximum seed production is almost always lower than for maximum biomass production. However, Donald (1963) reviewed yield-density relationships for corn, wheat, ryegrass, and subterranean clover and found maximum seed production and aboveground biomass occured at approximately the

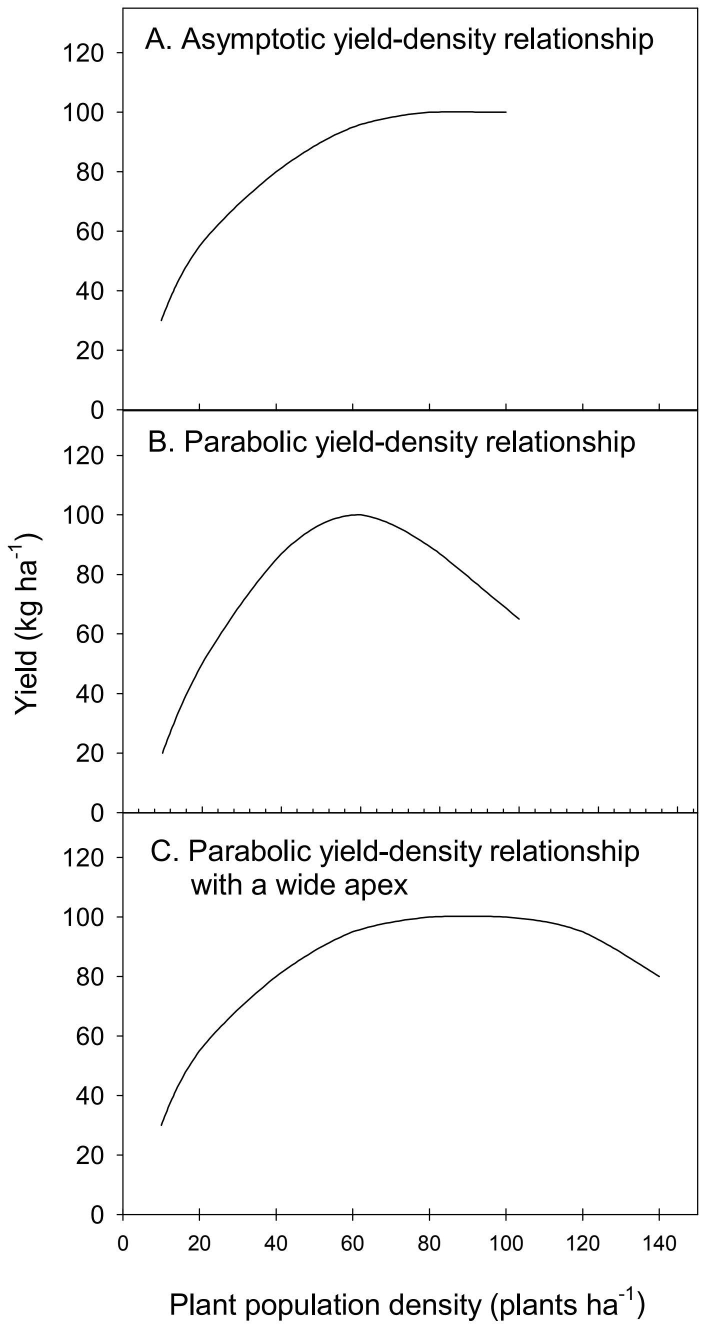

Figure 2.1: Graphical representation of yield-density relationships representing (A) an asymptotic yield-density response, (B) a parabolic yield-density response, and (C) a parabolic yield-density response with a wide apex.

same density. Donald (1963) went on to say that the current knowledge, in 1963, of the relationship between aboveground biomass and seed production was fragmented as few studies captured a wide enough range of plant population densities to capture the true relationship between density and yield for either seed or biomass production.

Recommended plant population densities could also be based on the density that minimizes weed yield. Increasing plant population densities have been demonstrated as an effective way to increase the ability of crops to compete with weeds (Mohler, 2001). Competition between plants occurs over resources including: light, water, nutrients, and carbon dioxide (Harper, 1977). Increasing the plant population density of a crop increases its proportional capture of resources compared to weeds and can result in increased crop yield and decreased weed yield (Mohler, 1996). The effectiveness of crop plant population density to increase weed control depends on the initial density of weeds and on the relative competitive abilities of crop and weeds (Mohler, 2001).

The yield-density response of crops is different under weedy and weed-free conditions (Blackshaw, 1993; Mohler, 2001). The maximum yield of a crop under weed-free conditions is usually higher than under weedy conditions. However, the plant population density where crop yield reaches its plateau is usually much higher under weedy conditions than under weed-free conditions. These differences are well illustrated in a two year study of the yield-density relationship of safflower (*Carthamus tinctorius* L.) (Blackshaw, 1993). The maximum shoot biomass of safflower over two growing seasons occurred above 70 and 84 plants m^{-2} under weed-free conditions, but this rose to 160 and 120 plants m^{-2} under weedy conditions. Also, the maximum seed yield of safflower over two growing seasons under weed-free conditions was approximately 200 and 250 g m^{-2}, while under weed-free conditions it was approximately 100 and 200 g m^{-2} (Blackshaw, 1993).

Although it is necessary to know the maximum biological yield of a crop when determining its recommended plant population densities, this knowledge gives no indication of profitability. This is an especially important consideration for asymptotic yield response curves where yield responses to increases in plant population density are very small at high densities and make it very costly to reach maximum biological yield. As well, plant population density recommendations based on maximum biological yield do not take into account possible increases in crop lodging or the occurrence of diseases as a result of increases in plant population density (Mohler, 2001). Thus, it would be more profitable to base plant population densities on optimizing economic returns.

2.5.2 Optimizing economic output

Optimum plant population density recommendations involve a trade-off between maximizing the value of crop yield and minimizing seed costs (Mohler, 2001). Seeding rate recommendations based on optimal economic production are determined using marginal cost analysis (eg. Browning and Zupan, 1999). This involves calculating seed costs and revenues from the sale of crop yield across a range of plant population densities. The plant population density at which the change in seed cost to grow one more plant per unit of area, is equal to the change in value of the yield per unit of area, is the economically optimum plant population density. This plant population density generates the greatest net revenues for crop production.

The relationship between marginal cost and marginal revenue can be depicted using different methods. The first considers the first derivative, or the slope, of the yield-density function as illustrated by French et al. (1994), Jettner et al. (1999), and Seymour et al. (2002). The point on the yield-density function where the slope is equal to the cost of increasing plant density by 1 plant m^{-2} ha^{-1} divided by the cost of selling the grain per unit of weight (eg. \$ kg^{-1} ha^{-1}) defines the optimum plant population density. The second method is to consider the relationships between seed cost and value of crop yield in terms of net revenue as illustrated by Shirtliffe and Johnston (2002). The difference between total revenue and total cost as plant population density increases results in a peaked curve. The density at which the peak occurs represents the most profitable production point, and thus is the optimum plant population density. Both methods take into account the relationship between seed cost and crop revenue and should produce the same seeding rate recommendations.

Both of these models take into account a 10% opportunity cost when calculating seed costs. Seymour et al. (2002) examined a range of opportunity costs from 10 to 100% to simulate a range in grower attitudes toward risk and their likely hood to spend an extra dollar on crop seeding rate compared to other farm inputs. They found that even large changes in opportunity cost had little impact on their optimum plant population density recommendations.

2.6 Relevance of green manure research to organic cropping systems

Organic producers growing green manure crops have benefited from new green manure crop varieties developed for green fallow and from research on the management of green fallow crops. However, it is debatable whether this research has been conducted under conditions that adequately represent the reality of organic cropping systems or has addressed their unique challenges.

Green manure crops are grown in rotation when soil nutrient reserves are depleted. A 2002 survey of 46 organic producers in Saskatchewan (Knight and Shirtliffe, 2003) found average soil nitrogen and phosphorous levels to be marginal at 19 kg N ha^{-1} for nitrogen (0 to 45 cm depth) and 17 kg P ha^{-1} for phosphorous (0 to 15 cm depth). However, in some green fallow experiments, phosphorous fertilizer was applied with the seed at rates of 20 to 24 kg P ha^{-1} (Biederbeck et al., 1993; Rice et al., 1993; Townley-Smith et al., 1993).

Weeds are present in both conventional and organic cropping systems. Chemical weed control was used in some green fallow studies either as a pre-plant incorporated treatment (Biederbeck et al., 1993; Biederbeck et al., 1996; Biederbeck et al., 1998) or as in-crop control (Janzen et al., 1990). Only Biederbeck et al. (1993) quantified the contribution of weed biomass to the experiment, however this was after a pre-plant treatment of trifluralin. Organic producers do not have this option, and it is very unlikely that conventional producers would incur the expense of a herbicide application for a green manure crop.

Renewed interest in organic production necessitates that adequate attention and resources are spent on research to address the challenges that limit the sustainability of this cropping system. Research focusing on basic agronomic recommendations, such as green manure crop plant population densities, species selection, and crop termination dates is needed to maximize the long-term benefits of green manure crops and to minimize their short-term disadvantages.

3.0 THE YIELD-DENSITY RELATIONSHIP OF CROP BIOMASS FOR THREE ANNUAL LEGUME GREEN MANURE CROPS UNDER WEEDY AND WEED-FREE CONDITIONS

3.1 Introduction

Organic cropping systems have always been reliant on cultural control methods to maintain weed control and contribute to soil fertility, of which green manuring is considered essential (Wallace, 2001). Green manure crops are grown for the purpose of incorporating their biomass into the soil, rather than for seed production. Weed control is one of the major challenges of organic cropping systems (Wallace, 2001), but little research has been conducted to address the contribution of green manure crops to weed control. Increasing plant population densities is an effective way to increase the competitive ability of crops with weeds (Mohler, 2001). Increasing the plant population density of a crop increases its proportional capture of resources compared to surrounding weeds and results in higher crop yields and lower weed biomass (Mohler, 1996).

Increasing crop plant population density is a common practice among organic producers to increase a green manure crop's competitive ability with weeds (Wallace, 2001). However, there are no published studies to support recommended plant population densities for annual legume green manure crops in the Northern Great Plains. Plant population densities for green manure crops currently used by organic producers may have been based on those developed for seed production of similar genotypes under weed-free and optimal nutrient conditions.

The yield-density response of a crop is different under weedy and weed-free conditions (Blackshaw, 1993; Mohler, 2001). The maximum yield of a crop under weedy conditions is typically lower than when grown under weed-free conditions (Blackshaw, 1993). However, the plant population density resulting in maximum crop yield is usually much higher under weedy conditions than under weed-free conditions (Blackshaw, 1993). Thus, it is unrealistic to assume that plant population densities determined under weed-free conditions are suitable for green manure crops grown under weedy conditions.

The effectiveness of increasing green manure plant population densities to control weeds depends on the crop's relative competitive ability (Mohler, 2001). The first report of differential competition with weeds among annual legume green manure crops was first published by Biederbeck et al. (1993). Field pea had the lowest percent weed biomass compared to black lentil, chickling vetch, and tangier flatpea (Biederbeck et al., 1993). However, green manure species were not compared at equivalent plant population densities nor across a range of densities and no justification was available for the plant population densities used. Mohler (2001) also suggests that the suppression of weeds from increases in crop density is greater when the density of weeds is higher.

Most green manure crop research conducted within the last 20 years has focused on their contribution to the fertility of subsequent crops and on their management to conserve soil moisture (Ladd et al., 1983; Biderbeck and Looman, 1985; Janzen et al., 1990; Rice et al., 1993; Townley-Smith et al., 1993; Biederbeck and Bouman, 1994; Zentner et al., 1996; Schlegel and Havlin, 1997; Vigil and Nielsen, 1998; Brandt, 1999; Bullied et al., 2002). Varieties of annual legume green manure crops have been developed for use as green manure crops to partially replace fallow in conventional annual cropping systems. These varieties include Indianhead black lentil (*Lens culinaris* Medikus), AC Green Fix chickling vetch (*Lathyrus sativus* L.) (Leyshon and Biederbeck, 1993), and Trapper field pea (*Pisum sativum* L.) (Ali-Khan and Kenaschuk, 1970). A 2002 survey of organic producers in Saskatchewan indicated that 5% had grown Indianhead black lentil as a green manure crop over the past 5 years, 5% had grown AC Green Fix chickling vetch, and 9% had grown peas (Knight and Shirtliffe, 2003). Although organic producers in Saskatchewan have taken advantage of these green manure crop varieties, research supporting basic agronomic management practices for green manure crops is not available.

Thus, this research endeavoured to determine optimum plant population densities for three annual green manure legumes under weedy and weed-free conditions, and to determine which species are best grown under weedy conditions. Based on the finding of Biederbeck et al. (1993), it was hypothesised that annual green manure legumes differ in their relative competitive ability with weeds, where competitive ability is defined as the ability of a plant to minimize weed biomass while maximizing its own biomass production. Excessive soil moisture use by green manure crops has been one of the major deterrents for their use in the Northern Great Plains (Pieters, 1917; Army and Hide, 1959; Brown, 1964; Biederbeck and Bouman, 1994). Soil moisture measurements were also included in this experiment to quantify soil moisture levels as green manure seeding rate increased in case a trade off had to be considered between minimizing soil moisture use and maximizing weed suppression. The objectives of this experiment were (1) to compare the competitive ability of field pea, chickling vetch, and black lentil with weeds and (2) to determine the biomass yield-density relationship for these three green manure crops under weedy and weed-free conditions. This information will be used in Chapter 5 to develop optimum plant population density recommendations for field pea, chicking vetch, and black lentil.

3.2 Materials and methods

3.2.1 Site description

Three experiments were conducted during the 2003 growing season, two at the Kernen Crop Research Farm (Kernen 1, Kernen 2) and one at the Saskatchewan Pulse Growers land (SPG). Both sites were located within the Dark Brown soil zone near Saskatoon, SK. As green manure crops in organic systems are usually grown at a point in the crop rotation when soil nutrient reserves have been depleted, soil tests were conducted to determine if soil nitrogen and phosphorous levels were appropriately low (Table 3.1). Soil tests were conducted by randomly sampling soil from 0 to 15 cm and 0 to 30 cm within the area of the intended experiments. Samples for each depth within each site were pooled, mixed, subsampled, and sent to Enviro

Table 3.1: Location, soil zone, and soil characteristics for the Kernen Crop Research Farm (Kernen) and the Saskatchewan Pulse Growers Land (SPG) near Saskatoon, SK.

Soil Characteristics	Kernen	SPG
Location	52°09'N 106°03W	52°04'N 106°12W
	NE 9-37-4 W3	NE 1-36-4 W3
Soil zone	Dark Brown	Dark Brown
Soil texture	Clay loam	Loam
pH	7.4	7.9
E.C. (mS cm^{-1})	0.2 (non saline)	0.2 (non saline)
Soil test nitrogen (kg ha^{-1})	24	13
Soil test phosphorous (kg ha^{-1})	73	26

Test Laboratories (Enviro Test Laboratories, Sakatoon, SK) for analysis. Soil nitrogen levels were near the Saskatchewan provincial average for organic farms of 19 kg N ha^{-1} (0 to 45 cm depth) (Knight and Shirtliffe, 2003). Soil phosphorous levels were above the provincial average of 17 kg P ha^{-1} (0 to15 cm depth) (Table 3.1). All green manure crops were seeded into wheat stubble.

3.2.2 Experimental and treatment design

The experiment was a three factor split-plot design with weed treatment as the main plot. Each main plot was split into 16 sub-plots for every combination of three green manure species and five target densities, as well as a weedy check plot. To keep main plot size balanced between both weedy and weed-free treatments, a guard plot was included in weed-free treatments. All sub-plots were fully randomized within the main plots for each of the four replicates. The two weed treatments for the main plots were weedy or weed-free. For weedy treatments, wild oat (*Avena fatua* L.) was planted at a target density of 50 plants m^{-2} and wild mustard (*Brassica kaber* (DC.) L.C. Wheeler) at a target density of 50 plants m^{-2} to supplement the natural weed community. The three green manure species used were field pea (*Pisum sativum* L. cv. Trapper), chickling vetch (*Lathyrus sativus* L. cv. AC Green Fix), and black lentil (*Lens culinaris* Medikus cv. Indianhead). The five target crop densities were 10, 24, 64, 160, 400 plants m^{-2}.

3.2.3 Seeding and plot management

All crops and weeds were seeded using a double disc press drill with a cone seeder. Both crop and weed seeding rates were adjusted for germination test results and a 20% seedling mortality rate was assumed for weeds. Field pea, black lentil, and chickling vetch were all treated with recommended amounts of the appropriate peat based *Rhizobium* inoculant (Becker Underwood, Saskatoon, SK, Canada). Plot size was 2 x 5 m for all locations and row spacing was 20 cm. No fertilizer was applied.

Originally only two experiments were to be run during the 2003 season. However, a mechanical malfunction with the seeder required that both locations be reseeded. At SPG plants from the first seeding date were killed with a treatment of glyphosate, but at Kernen the first seeding date of the experiment was kept as less than one quarter of the experiment was affected. Thus, three experiments are included in the following analysis. These three experiments spanned two sites, and within the Kernen site are separated in time by two weeks. In order to provide at least 3 replicates of all treatments in the Kernen 1 experiment, plots in the fourth rep were thinned from higher to lower plant population densities as required. However, it was not possible to obtain three replicates of all treatments in the Kernen 1 experiment. Missing plots were accounted for in the statistical analysis by using the mixed procedure of SAS (Little et al., 1996).

At the first seeding date (May 20 and 21, 2003) soil moisture conditions were favourable. Wild mustard was seeded at a depth of 1.2 cm and wild oat at 2.5 cm. Field pea, black lentil and chickling vetch were seeded 2.5 cm deep. The weeds were seeded before the crop to accommodate different planting depths and then cultivated perpendicularly to the seed rows in order to distribute weed seeds. Weed-free plots were given the same tillage treatments and guard plots between weedy and weed-free main plots was used to prevent contamination during tillage.

At the second seeding date (June 1 and 4, 2003) soil moisture conditions were less favourable. Thus, crop and weeds were seeded at the same time in separate rows and the tillage treatment to disperse the weeds was eliminated to conserve soil moisture. Pre-emergence glyphosate treatments were used to control weeds in all experiments. In weed-free treatments, grassy weeds were controlled using sethoxydim (Post Ultra) and broadleaf weeds were controlled using hand weeding.

3.2.4 Measurements

3.2.4.1 Biomass and plant population densities

Above ground biomass was harvested for each species during their respective early bud and full bloom stages (Table 3.2). For the purposes of this experiment, the early bud stage of each green manure species occurred when 90% of plants had formed buds. The full bloom stage occurred when 90% of plants had flowered. A randomly placed 0.25 m^2 quadrate was harvested from the front and back of each plot. In weedy treatments, biomass for the green manure crop, wild mustard, wild oat, and other weeds were collected separately. Biomass samples were dried at 60^{o}C for 72 hours. Plant densities for both crop and weeds were measured during the biomass harvest at the early bud stage.

Table 3.2: Harvest dates for three green manure species at their respective early bud and full bloom stages during the 2003 growing season at Kernen 1, Kernen2, and SPG.

	Chickling vetch		Field pea		Black lentil	
Location	Early bud	Full bloom	Early bud	Full bloom	Early bud	Full Bloom
Kernen 1	July 3	July 11	July 11	July 18	July 16	July 23
Kernen 2	July 18	July 31	July 24	Aug 1	July 25	Aug 5
SPG	July 16	July 31	July 23	Aug 1	July 25	Aug 5

3.2.4.2 Soil moisture

Volumetric soil moisture measurements were taken using Time Domain Reflectometry (TDR) (Topp et al., 1982). Measurements were made using a Tektronix 1502B metallic cable tester (Tektronix, Wilsonville, OR). Pairs of stainless steel rods in three lengths, 15 cm, 30 cm, and 60cm, were inserted vertically into the middle of the plots between seed rows at Kernen 2 and SPG experiments. Fifteen cm rods measured soil moisture from the 0 to 15 cm depth, 30 cm rods from the 0 to 30 cm depth, and 60 cm rods from the 0 to 60 cm depth. Measurements were made in every plot during the period of early bud and full bloom for all green manure species (Table 3.3).

Table 3.3: Sampling dates for soil moisture during early bud and full bloom stages for three green manure crops grown at Kernen 2 and SPG.

Location	Early bud	Full bloom
Kernen 2	July 22	Aug 8
SPG	July 25 - 26	Aug 8

3.2.5 Statistical analysis

3.2.5.1 Green manure and weed biomass

Non-linear regression analysis was performed on all crop and weed biomass data using the non-linear procedure of SAS (SAS Institute Inc., 1989). Using non-linear regression enabled the model to account for actual plant population densities, rather than just target plant population densities. Crop biomass was described by the equation:

$$BM_{gm} = (D_{gm} * W_m / (1 + a * D_{gm})) * 10 \qquad [3.1]$$

where BM_{gm} is green manure crop biomass in kg ha^{-1}, D_{gm} is the observed green manure plant density in plants m^{-2}, W_m is the maximum potential biomass per green manure plant in kg ha^{-1} at very low densities, and a is the soil surface area needed to achieve W_m in m^2 (Aikman and Watkinson, 1980). Ten is a factor to convert from green manure biomass in g m^{-1} to kg ha^{-1}. Weed biomass was described by the equation:

$$BM_w = (Y_{max} * (1 – (r_{max} * D_{gm}) / (1 + (y * D_{gm}))*10 \quad [3.2]$$

where BM_w is weed biomass in kg ha^{-1}, Y_{max} is the maximum potential weed biomass in kg ha^{-1} as crop density approaches zero, r_{max} is the slope of the change in weed biomass as green manure plant population density increases, y is the minimum weed biomass yield in kg ha^{-1} as crop density approaches infinity, and D_{gm} is the green manure plant population density in plants m^{-2} (modified from Cousens, 1985). Ten is a conversion factor to convert from weed biomass in g m^{-1} to kg ha^{-1}.

An approximation of the coefficient of determination (R^2) for all crop and weed biomass non-linear regression equations was calculated using the following equation:

$$Pseudo\ R^2 = 1 – SS(Residual) / SS\ (Total_{Corrected}) \quad [3.3]$$

where *SS(Residual)* is the residual sum of squares and $SS\ (Total_{Corrected})$ is the corrected total sum of squares for the non-linear regression (Jasieniuk et al,. 1999).

Extra sum of squares tests were used to compare the parameters of the equations used to describe crop and weed biomass production among different locations and combinations of treatments (Lindquist et al., 1996). When extra sum of squares tests indicated significant differences in equation parameters among weed treatments and harvest dates, ninety-five percent confidence intervals for the means of each species within weed treatments or harvest dates were used to determine if parameter estimates were significantly different among green manure species (Lindquist et al., 1996).

3.2.5.2 Soil moisture

Volumetric soil moisture was calculated using the Topp equation:

$$\theta_v = (0.1138 * \sqrt{\Sigma_a}) * 100 \quad [3.4]$$

where θ_v is volumetric soil moisture in %, 0.1138 is a constant, and Σ_a is the dielectric constant of the soil (Topp et al., 1982). The dielectric constant is calculated using the equation:

$$\Sigma_a = [L_1 - L_2 / L]^2 \quad [3.5]$$

where Σ_a is the dielectric constant, L_1 is the length of the transmission line in m when the signal enters in the soil, L_2 is the length of the transmission line in m when the signal returns to the probe, and L is the length of the stainless steel rod inserted into the soil in m (Topp et al., 1982).

A mixed model was used to test for significant differences in soil moisture between crops and target plant population densities using the mixed procedure of SAS (Littell et al., 1996). The analysis was performed on the combined data from both sites and on each site individually. Site and blocks were considered random while weed treatment, green manure species, green manure target plant population density and harvest treatment were considered fixed.

3.3 Results and Discussion

3.3.1 Environmental conditions

The 2003 growing season was extremely dry and followed two previous years of drought. Precipitation in April of 2003 was higher than the long-term average and provided good soil moisture going into the 2003 growing season (Table 3.4). However, precipitation for May and June were 32 and 50% of the long-term average, respectively. The majority of precipitation for each month from May untill August fell primarily on one or two days within each month (data not shown). Thus stored soil moisture was critical for maintaining plant growth during the growing season. Mean monthly air temperatures were close to long-term averages (Table 3.4). Temperatures during June and July are typically high, creating high evaporative and transpirational demands during the period of most significant green manure crop growth.

3.3.2 Plant emergence and population density

All green manure crops emerged 8 to 12 days after planting (data not shown). Chickling vetch was the first species to reach the early bud stage, followed by field

Table 3.4: Monthly precipitation and mean monthly air temperature from September 2002 to August 2003 and their long-term averages (1971-2000) at the Kernen Crop Research Station near Saskatoon, SK.

Precipitation	Sep	Oct	Nov	Dec	Jan	Feb	Mar	April	May	June	July	Aug
	mm											
2003	59.0	14.5	3.8	20.4	8.0	.	5.2	61.2	13.8	30.8	63.9	31.4
Long-term average	30.6	16.9	13.7	18.9	17.9	13.1	16.2	24.2	43.6	60.5	57.3	35.4
Air Temperature												
	°C											
2003	10.8	-1.6	-5.2	-9.4	-17.6	.	-9.9	4.6	11.8	15.9	18.2	20.6
Long term average	11.5	4.8	-5.6	-13.9	-16.4	-12.5	-5.6	4.7	11.8	16.0	18.3	17.6

pea and then black lentil. The first cohort of wild oat, wild mustard, and the natural weed community emerged with the green manure crops. Other cohorts of weeds germinated in June and July following precipitation events. The average number of days for each species to reach the early bud and full boom stages are listed in Table 3.5. Chicking vetch was the first species reach both early bud and full bloom stages followed by field pea and then black lentil (Table 3.5). The average number of days between the early bud and full bloom stage were 12, 8, and 7 days for chickling vetch, field pea, and black lentil respectively. Despite drought conditions, timely rainfall allowed all green manure crops to reach the early bud and full bloom stages without showing signs of drought stress.

Crop densities and percent crop emergence are listed in Table 3.6. Percent crop emergence was higher at lower plant population densities. Percent crop emergence was greater than 100% at lower plant population densities. This was most likely due to sampling bias and underestimation of the percent germination of seed used for Kernen 2 and SPG. Because new seed had to be ordered to seed Kernen 2 and to reseed SPG, there was no time to conduct germination tests to confirm the percent germination of the seed lots provided by the seed companies.

Weed densities are listed in Table 3.7. The natural weed communities (other weeds), namely green foxtail (*Setaria viridis* L.) and volunteer wheat (*Triticum aestivum* L.), made significant contributions to weed biomass in all three experiments.

3.3.2 Extra sum of squares test for crop and weed biomass

Extra sum of squares tests and covariance tests confirmed that it was appropriate to combine crop biomass from all three sites for analysis (Table 3.8). The null hypothesis that equation parameters W_m and a do not vary among locations was accepted for both the early bud and full bloom harvest stage. Extra sum of squares tests were also performed on weed biomass data to determine if it was appropriate to combine weed data from all three sites for analysis (Table 3.9). The null hypothesis that there were no significant differences among the Y_{max}, r_{max}, and y parameters was accepted for the early bud harvest stage but not for the full bloom

Table 3.5: Average number of days after planting to reach early bud and full bloom for chickling vetch, field pea, and black lentil for Kernen1, Kernen 2, and SPG combined.

Harvest Date	Chickling vetch	Standard error	Field pea	Standard error	Black lentil	Standard error
	Days					
Early Bud	44	1.4	51	1.4	54	1.4
Full Bloom	56	1.4	59	1.4	63	1.4

Table 3.6: Target plant population densities, average observed plant population densities, and average percent emergence for weedy and weed-free treatments of field pea, chickling vetch, and black lentil green manure crops for Kernen 1, Kernen 2, and SPG combined.

Observed plant population density	Target plant population density (plants m^{-2})	Field pea	Standard error	Chickling vetch	Standard error	Black lentil	Standard error
		plants m^{-2}					
Weedy	10	15	10	27	10	14	10
	24	33	10	36	10	23	10
	64	75	10	98	10	69	10
	160	143	10	187	10	158	10
	400	340	10	354	10	338	10
Weed-free	10	14	9	17	10	15	10
	24	36	9	37	10	31	10
	64	92	10	90	10	77	10
	160	175	10	202	10	151	10
	400	342	10	365	10	342	10
Percent emergence							
		%					
Weedy	10	154	25	271	24	143	24
	24	136	24	152	24	97	24
	64	117	24	153	24	108	24
	160	90	25	117	24	99	25
	400	85	24	88	24	84	24
Weed-free	10	138	23	174	24	152	24
	24	149	23	153	24	131	24
	64	144	24	141	24	120	24
	160	109	25	126	24	95	24
	400	86	24	91	24	85	25

Table 3.7: Target green manure plant population densities and average observed weed population densities in field pea, chickling vetch, and black lentil green manure crops for Kernen 1, Kernen 2, and SPG combined.

Weed type	Green manure target plant population density (plants m^{-2})	Field pea	Standard error	Chickling vetch	Standard error	Black lentil	Standard error
		plants m^{-2}					
Wild mustard	10	10	4	8	4	9	4
	24	10	4	8	4	13	4
	64	9	4	6	4	8	4
	160	5	4	9	4	16	4
	400	4	4	5	4	6	4
Wild oat	10	21	7	51	7	38	7
	24	30	7	26	7	39	7
	64	20	7	33	7	41	7
	160	18	7	28	7	30	7
	400	15	7	25	7	24	7
Other weeds	10	274	42	286	41	216	41
	24	218	41	305	41	231	41
	64	178	41	238	41	158	41
	160	104	42	214	42	101	41
	400	54	41	134	41	52	41
All weeds	10	305	38	275	37	332	37
	24	258	37	265	37	335	37
	64	202	37	198	37	279	37
	160	127	38	138	37	251	38
	400	73	37	82	37	166	37

Table 3.8: Extra sum of squares test results for green manure crop biomass equation parameters.

	H_o[a] = W_m[b] and a[c] do not vary			H_o[d] = W_m does not vary			H_o[e] = a does not vary		
Among locations (Kernen 1, Kernen 2, SPG)	df_n[f]	df_d[g]	F_{cal}[h]	d_{fn}	d_{fd}	F_{calc}	d_{fn}	d_{fd}	F_{calc}
Early bud	4	321	1.85	-[i]	-	-	-	-	-
Full bloom	4	320	1.20	-	-	-	-	-	-
Between weed treatments (Weedy and weed-free)									
Field pea – early bud	2	105	6.39*	2	105	0.00	2	105	6.23*
Field pea – full bloom	2	105	15.40*	2	105	9.93*	2	105	6.82*
Chickling vetch – early bud	2	106	1.32	-	-	-	-	-	-
Chickling vetch – full bloom	2	105	8.66*	2	105	5.47*	2	105	3.86*
Black lentil – early bud	2	104	20.92*	2	104	8.85*	2	104	3.90*
Black lentil – full bloom	2	104	38.22*	2	104	13.41*	2	104	5.82*
Among species (field pea, chickling vetch, and black lentil)									
Weedy – early bud	4	156	45.94*	3	156	12.95*	3	156	2.16
Weedy – full bloom	4	156	26.01*	3	156	11.19*	3	156	4.13*
Weed-free – early bud	4	159	47.62*	3	159	26.12*	3	159	61.25*
Weed-free – full bloom	4	158	8.41*	3	158	4.27*	3	158	2.68*
Between harvest dates (early bud and full bloom)									
Field pea – weedy	2	102	13.00*	2	102	2.76	2	102	2.50
Field pea – weed-free	2	108	37.23*	2	108	3.78*	2	108	2.44
Chickling vetch - weedy	2	106	32.32*	2	106	20.82*	2	106	1.57
Chickling vetch – weed-free	2	105	42.87*	2	105	53.95*	2	105	7.33*
Black lentil - weedy	2	104	13.48*	2	104	1.09	2	104	0.011
Black lentil – weed-free	2	104	42.92*	2	104	8.07*	2	104	1.76

[a] Indicates null hypothesis that crop biomass equations do not differ because of either W_m or a
[b] W_m is the maximum potential biomass per green manure plant at very low densities
[c] a is the soil surface area needed to achieve W_m
[d] Indicates null hypothesis that W_m does not differ between crop biomass equations
[e] Indicates null hypothesis that a does not differ between crop biomass equations
[f] Numerator degrees of freedom
[g] Denominator degrees of freedom
[h] Calculated F-value
[i] Dash indicates that parameter tests for W_m or a were not required as null hypothesis that crop biomass equations do not differ because of either W_m or a was accepted
* Significantly different (P = 0.05)

Table 3.9: Extra sum of squares test results for weed biomass equation parameters.

Among experiments (Kernen 1, Kernen 2, and SPG)	$H_o{}^a = Y_{max}{}^b$, $r_{max}{}^c$, and Y^d do not vary			$H_o{}^e = Y_{max}$ does not vary			$H_o{}^f = r_{max}$ does not vary			$H_o{}^g = Y$ does not vary		
	$d_{fn}{}^h$	$d_{fd}{}^i$	$F_{calc}{}^j$	d_{fn}	d_{fd}	F_{calc}	d_{fn}	d_{fd}	F_{calc}	d_{fn}	d_{fd}	F_{calc}
Early bud	6	153	1.56	-[k]	-	-	-	-	-	-	-	-
Full bloom	5	154	6.84*	2	154	7.11*	2	154	1.77	2	154	1.18
Between harvest dates (early bud, full bloom)												
Field pea	3	100	7.64*	2	100	3.97*	2	100	0.11	2	100	0.13
Chickling vetch	3	104	23.52*	3	104	5.56*	2	104	0.0024	2	104	0.014
Black lentil	2	103	42.75*	2	103	16.30*	1	103	0.57	1	103	42.97*
Among green manure species (field pea, chickling vetch, and black lentil)												
Early bud	5	154	31.15*	3	154	11.85*	2	154	2.96	2	154	1.79
Full bloom	6	153	12.66*	4	153	2.70*	3	153	0.68	3	153	0.29

[a] Indicates null hypothesis that crop biomass equations do not differ because of Y_{max}, r_{max}, or Y
[b] Y_{max} is the maximum potential weed biomass as crop density approaches zero
[c] r_{max} is the slope of the change in weed biomass as green manure plant population density increases
[d] Y is the minimum weed biomass yield as crop density approaches infinity
[e] Indicates null hypothesis that Y_{max} does not differ between weed biomass equations
[f] Indicates null hypothesis that r_{max} does not differ between weed biomass equations
[g] Indicates null hypothesis that Y does not differ between weed biomass equations
[h] Numerator degrees of freedom
[i] Denominator degrees of freedom
[j] Calculated F-value
[k] Dash indicates that parameter tests for W_m or a were not required as null hypothesis that weed biomass equations do not differ because of Y_{max}, r_{max}, or Y was accepted
* Significantly different ($P = 0.05$)

harvest stage (Table 3.9). Specifically, the parameter Y_{max} representing the maximum potential weed biomass differed among experiments at full bloom. Using a combined analysis under these circumstances increased the risk of making a type two error, which is not finding a difference between treatments when there was a difference. However, combining the weed data in an extra sum of squares tests between green manure species at the full bloom stage revealed significant difference in the Y_{max} parameter. Furthermore, extra sum of squares tests for crop biomass confirmed differences in W_m and a parameters among green manure weed treatments, harvest, and crop species (Table 3.8). Extra sum of squares tests for weed biomass confirmed differences in Y_{max} and y parameters among green manure harvest dates and green manure species (Table 3.9).

3.3.3 Crop biomass

Green manure crop biomass production increased across all plant population densities under both weedy and weed-free treatments (Figures 3.1 to 3.4). Differences among treatments can be compared using the two parameters, W_m and a, used in the equations describing biomass accumulation of green manure crops (Equation 3.1). Extra sum of squares tests indicated that equation parameters for green manure crop biomass differed among harvest dates, green manure species, and weed treatments, because the null hypothesis that parameters W_m and a do not vary among treatments was rejected (Table 3.8). However, an exception occurred when comparing weedy vs. weed-free treatments of chickling vetch at early bud (Table 3.8). This exception can be seen when examining biomass accumulation curves for chickling vetch in Figure 3.1-B and 3.2-B.

The parameter W_m represents maximum biomass production per individual plant and influences the biomass function plateau. Comparisons between harvest dates revealed differences in W_m for all combinations of species and weed treatments except for black lentil and field pea under weedy conditions (Table 3.8). Where W_m was significantly different between harvest dates, it was higher at the full bloom stage than at the early bud stage for both weed treatments (Table 3.8 and 3.10).

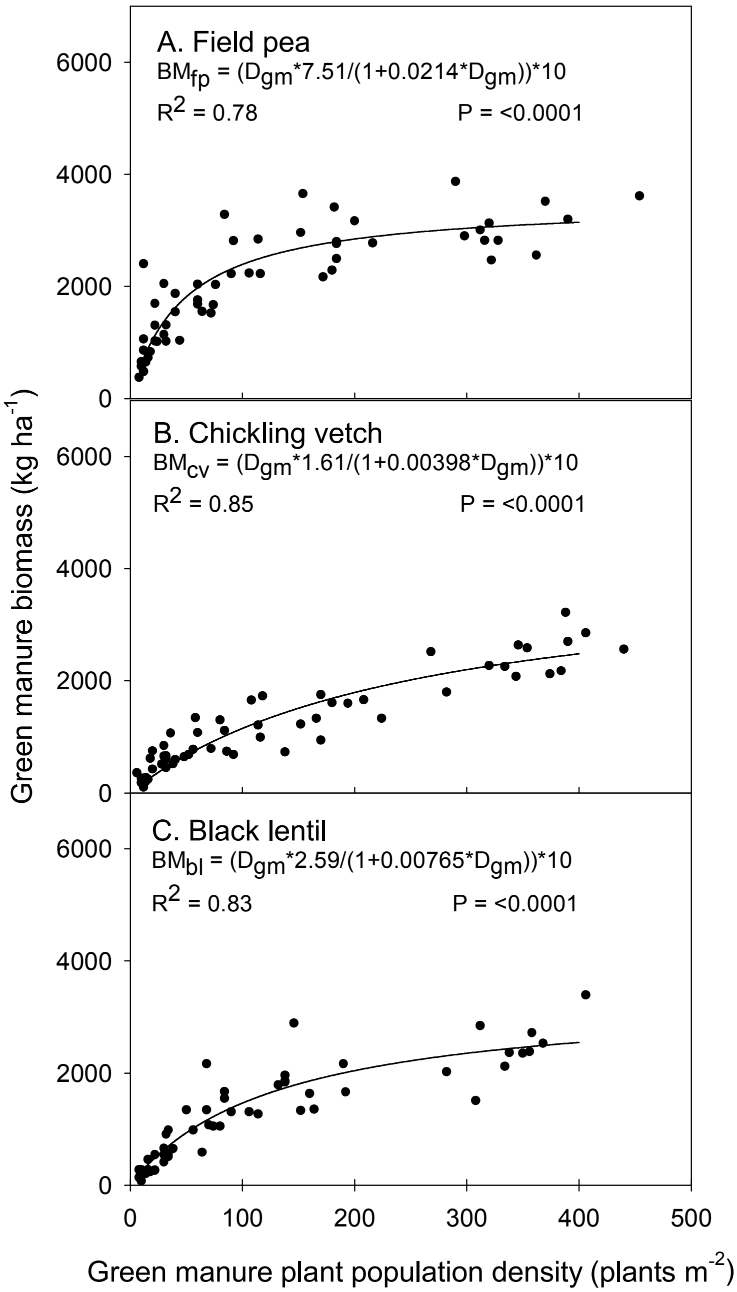

Figure 3.1: Effect of plant population density on green manure crop biomass accumulation in (A) field pea, (B) chickling vetch, and (C) black lentil under weed-free conditions at early bud. Curves are based on the equation $BM_{gm} = (D_{gm}*W_m / (1 + a*D_{gm}))*10$, where BM_{gm} is green manure crop biomass in kg ha^{-1}, D_{gm} is the observed green manure plant density in plants m^{-2}, W_m is the maximum potential biomass per green manure plant in kg ha^{-1} at very low densities, and a is the soil surface area needed to achieve W_m in m^2 (Aikman and Watkinson, 1980). Ten is a conversion factor to convert from weed biomass in g m^{-1} to kg ha^{-1}.

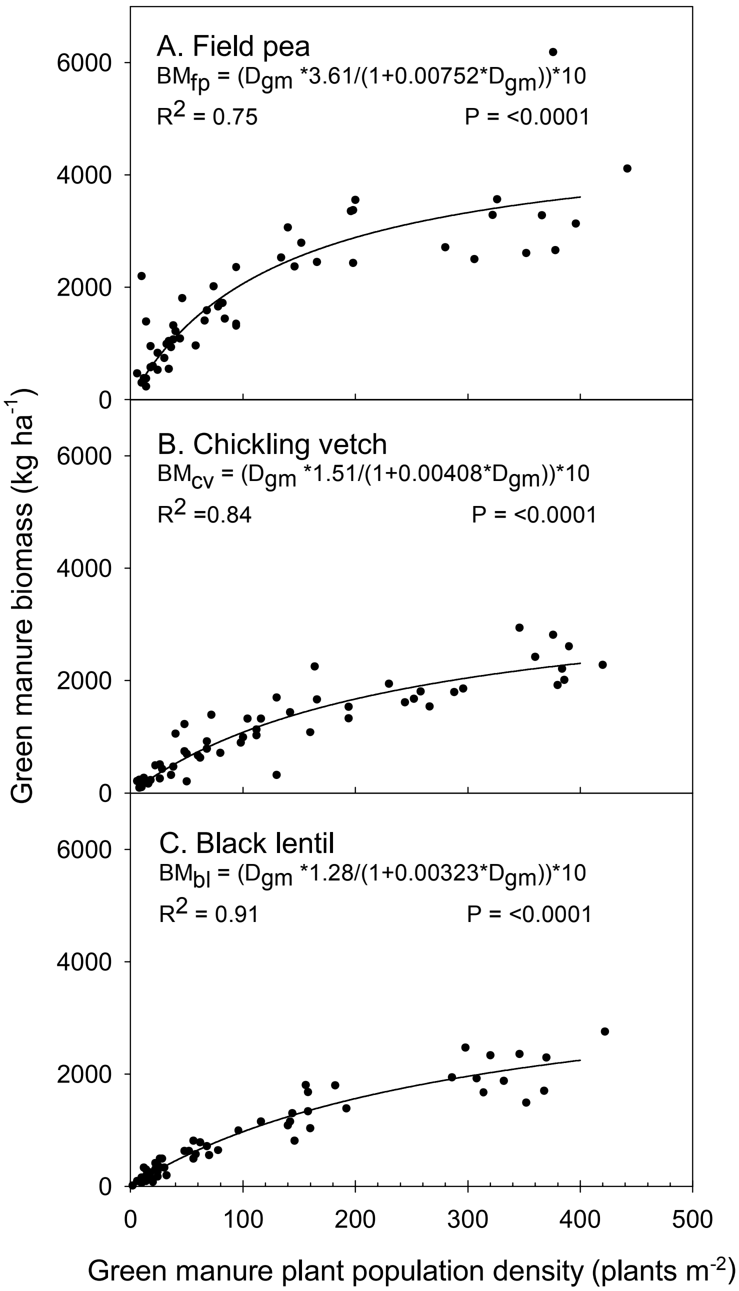

Figure 3.2: Effect of plant population density on green manure crop biomass accumulation in (A) field pea, (B) chickling vetch, and (C) black lentil green manure crops under weedy conditions at early bud. Curves are based on the equation $BM_{gm} = (D_{gm}*W_m / (1 + a*D_{gm}))*10$, where BM_{gm} is green manure crop biomass in kg ha^{-1}, D_{gm} is the observed green manure plant density in plants m^{-2}, W_m is the maximum potential biomass per green manure plant in kg ha^{-1} at very low densities, and a is the soil surface area needed to achieve W_m in m^2 (Aikman and Watkinson, 1980). Ten is a conversion factor to convert from weed biomass in g m^{-1} to kg ha^{-1}.

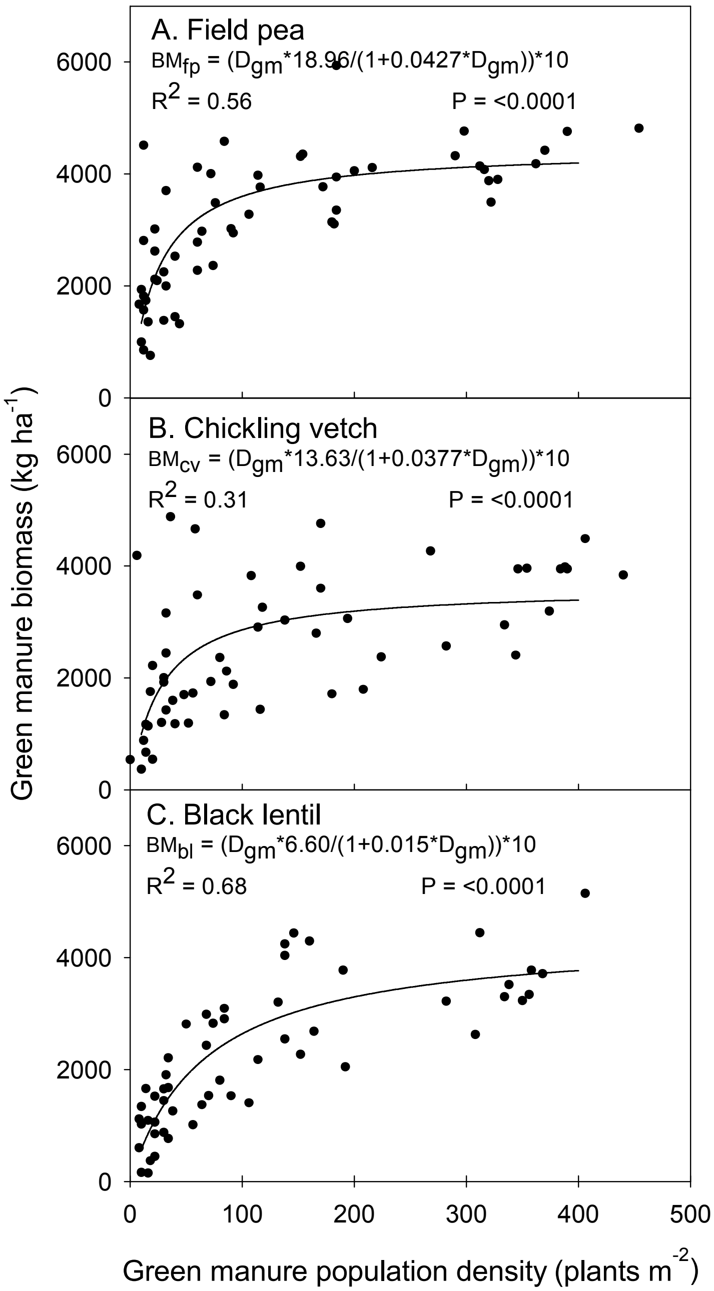

Figure3.3: Effect of plant population density on green manure crop biomass accumulation in (A) field pea, (B) chickling vetch, and (C) black lentil green manure crops under weed-free conditions at full bloom. Curves are based on the equation $BM_{gm} = (D_{gm}*W_m / (1 + a*D_{gm}))*10$, where BM_{gm} is green manure crop biomass in kg ha^{-1}, D_{gm} is the observed green manure plant density in plants m^{-2}, W_m is the maximum potential biomass per green manure plant in kg ha^{-1} at very low densities, and a is the soil surface area needed to achieve W_m in m^2 (Aikman and Watkinson, 1980). Ten is a conversion factor to convert from weed biomass in g m^{-1} to kg ha^{-1}.

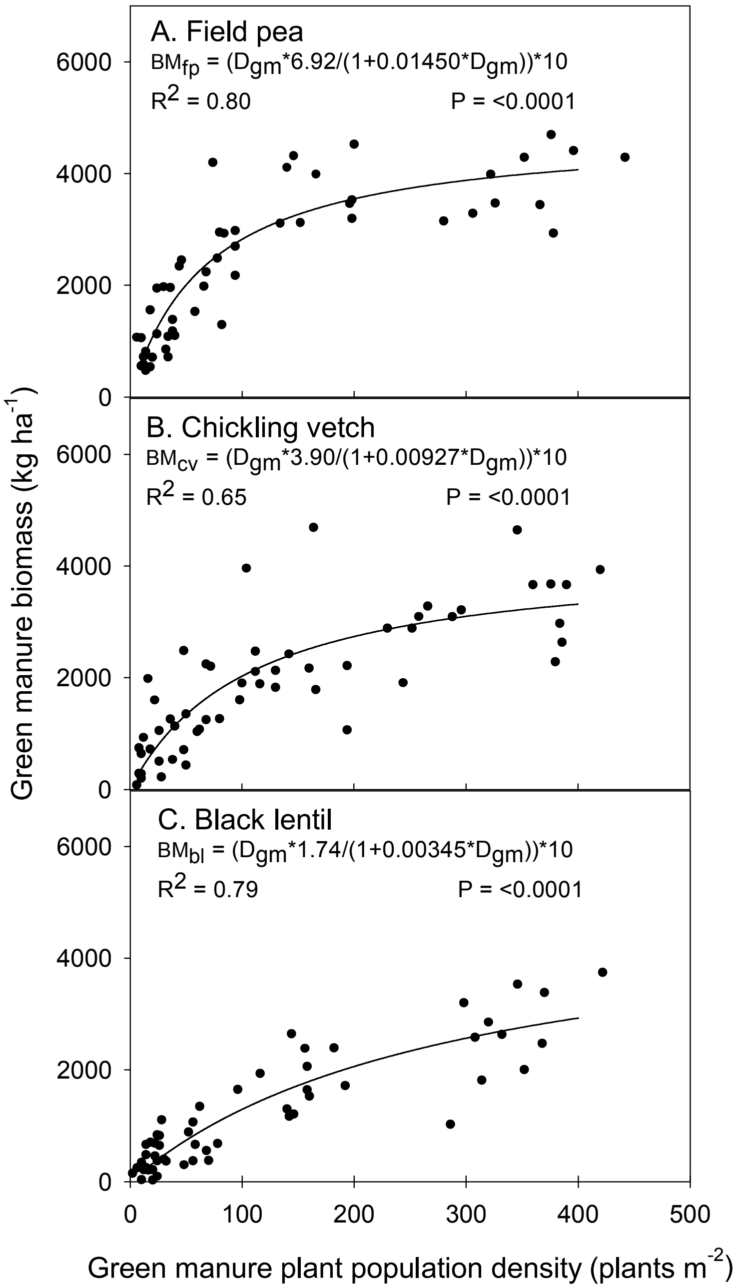

Figure 3.4: Effect of plant population density on green manure crop biomass accumulation in (A) field pea, (B) chickling vetch, and (C) black lentil green manure crops under weedy conditions at full bloom. Curves are based on the equation $BM_{gm} = (D_{gm}*W_m / (1 + a*D_{gm}))*10$, where BM_{gm} is green manure crop biomass in kg ha^{-1}, D_{gm} is the observed green manure plant density in plants m^{-2}, W_m is the maximum potential biomass per green manure plant in kg ha^{-1} at very low densities, and a is the soil surface area needed to achieve W_m in m^2 (Aikman and Watkinson, 1980). Ten is a conversion factor to convert from crop biomass in g m^{-1} to kg ha^{-1}.

Table 3.10: Estimates and standard errors of W_m and a equation parameters for green manure crop biomass at early bud and full bloom under weedy and weed-free conditions.

	W_m [a]				a [b]			
	Early bud		Full bloom		Early bud		Full bloom	
Weed-free	Estimate	Standard error	Estimate	Standard error	Estimate	Standard error	Estimate	Standard error
Field pea	7.51a*	0.985	18.96	3.414	0.0214b	0.003660	0.0427a	0.00930
Chickling vetch	1.61b	0.184	13.64	4.072	0.00398a	0.000883	0.0377ab	0.01370
Black lentil	2.59ab	0.314	6.60	1.108	0.00765a	0.001530	0.015b	0.00355
Weedy								
Field pea	3.61a	0.535	6.92a	0.881	0.00752	0.001800	0.01450a	0.002600
Chickling vetch	1.52b	0.184	3.90a	0.753	0.00408	0.000967	0.00927ab	0.002710
Black lentil	1.29b	0.126	1.74b	0.273	0.00323	0.000692	0.00345b	0.001140

[a] W_m is the maximum potential biomass per green manure plant at very low densities
[b] a is the soil surface area needed to achieve W_m
* Letters indicate significantly different estimates within columns and weed treatments (P = 0.05)

Comparisons between weed treatment also revealed differences in W_m. Green manure species differed in biomass production between weed treatments for both harvest dates with the exception of chickling vetch and field pea at the early bud stage (Table 3.8) (Figure 3.1 to 3.4). Where W_m was significantly different between weed treatments, it was higher under weed-free conditions (Table 3.10).

Differences in W_m were found among species and were influenced by both harvest date and weed treatment (Table 3.8). Field pea produced the most biomass of all three species at comparable densities (Figure 3.1 to 3.4). This was reflected in the higher values of W_m for field pea at the early bud stage compared to chickling vetch or black lentil under both weedy and weed-free conditions (Table 3.10). At full bloom the W_m of field pea was significantly different from black lentil but not chickling vetch under weedy conditions (Table 3.10). No difference among species occurred under weed-free conditions at full bloom.

Black lentil and chickling vetch produced similar amounts of biomass (Figure 3.1 to 3.4) as reflected by their the W_m values for all treatments with the exception of weedy conditions at full bloom (Table 3.10). Differences between the W_m of chickling vetch and black lentil were influenced by harvest stage and weed treatment. At early bud, the W_m of chickling vetch and black lentil do not differ under either weed treatment. However, at full bloom, the W_m of chickling vetch and black lentil are significantly different only under weedy conditions (Table 3.10) (Figure 3.4). This indicates that chickling vetch is able to produce more biomass than black lentil at equivalent densities and suggests that chickling vetch is better able to compete with weeds.

The parameter a represents the soil surface area required to achieve W_m and influences the initial slope of the biomass function. As the number of plants per unit area increases, a larger value of a allows crop biomass to accumulate more rapidly towards its asymptote. The value of a was found to vary among green manure species, except under weedy conditions at early bud (Table 3.8). Weed treatment and harvest stage influenced differences between green manure species (Table 3.10). Chickling vetch and black lentil did not have significantly different a values under either weedy or weed-free conditions at early bud. The value of a for field pea at early bud was significantly different from chickling vetch and black lentil under weed-free conditions (Table 3.10). At full bloom, the *a* value of field pea was significantly different from black lentil, but not from chickling vetch under both weedy and weed-free conditions (Table 3.10).

Significant differences in *a* were found among weed treatments. The value of *a* was higher for weed-free treatments in field pea and black lentil at both the early bud and full bloom stages (Table 3.8 and 3.10). However, significant differences in *a* among weed treatments for chickling vetch were only seen at the full bloom stage (Table 3.8). This lack of a difference at the early bud stage suggests that chickling vetch is behaving similarly under weedy and weed-free conditions and that it is better able to tolerate weed competition at this early stage.

Harvest date had little influence on the value of *a* (Table 3.8). The only significant difference in *a* between the early bud and full bloom stages was found in chickling vetch under weed-free conditions (Table 3.8 and 3.10). This suggests that it takes a longer time for chickling vetch to accumulate biomass and that the rate of biomass accumulation for field pea and black lentil is more consistent over time between the early bud and full bloom stages.

The relative ability of each species to produce biomass found in this study can be compared to the results of Biederbeck et al. (1993). Their study found feed pea to produce an average dry matter of 2628 kg ha^{-1} at full bloom followed by chickling vetch at 1790 kg ha^{-1} and black lentil at 1478 kg ha^{-1} under weedy conditions. It should be noted that these results were obtained when plots were fertilized with phosphorous to meet soil test recommendations in the Brown soil zone. Target stand densities for the Biederbeck et al. (1993) study were 62 plants m^{-2} for feed pea, 55 plants m^{-2} for chickling vetch, and 140 plants m^{-2} for black lentil. At these same densities, biomass production in this study at the full bloom stage under weedy conditions was lower for field pea and chickling vetch at 2250 kg ha^{-1} and 1400 kg ha^{-1} respectively. Biomass for black lentil at the full bloom stage under weedy conditions was higher at 1640 kg ha^{-1}. In both studies field pea produced the most biomass. For the densities used in the Biederbeck et al. (1993) study, they found chickling vetch to accumulated more biomass relative to black lentil, while the reverse was seen in this study at full bloom for the specified densities. However, when comparing chickling vetch and black lentil at equivalent densities, this study found that chickling vetch accumulated more biomass than black lentil when grown at either 55 plants m^{-2} or 140 plants m^{-2}.

Other studies have reported biomass accumulation of annual legume green manure crops. Few compare biomass production among different green manure species. Townley-Smith et al. (1993) reported biomass production for field pea at 6390 kg ha^{-1} and black lentil at 4140 kg ha^{-1} in the Dark Brown soil zone when terminated at full bloom. Plant population densities used in this experiment were not given and phosphorous fertilizer was placed with the seed.

3.3.4 Weed biomass

Increasing green manure plant population density resulted in decreased weed biomass production in all treatments (Figure 3.5 and 3.6). Differences among weeds growing with different green manure species and harvested at different green manure plant stages can be compared using the three parameters, Y_{max}, r_{max}, and y, used in the equation describing weed biomass accumulation as green manure crop plant population density increases (Equation 3.2). The variable r_{max}, describing the slope of the change in weed biomass as green manure plant population density increases, does not significantly differ between harvest dates or among green manure species (Table 3.9).

The variable y, describing minimum weed biomass accumulation, only varied between early bud and full bloom for black lentil (Table 3.9). This reflects the higher amount of weed biomass accumulation for black lentil at full bloom compared to early bud (Figure 3.5 vs. 3.6). The absence of significant differences in y for chickling vetch and field pea suggest that they are better able to compete with weeds, as there is less change in their weed biomass between early bud and full bloom.

The variable Y_{max} represents the maximum weed biomass production or the y-intercept as green crop density approaches zero. Y_{max} was consistently different among harvest dates and all green manure species (Table 3.9). The values for Y_{max}

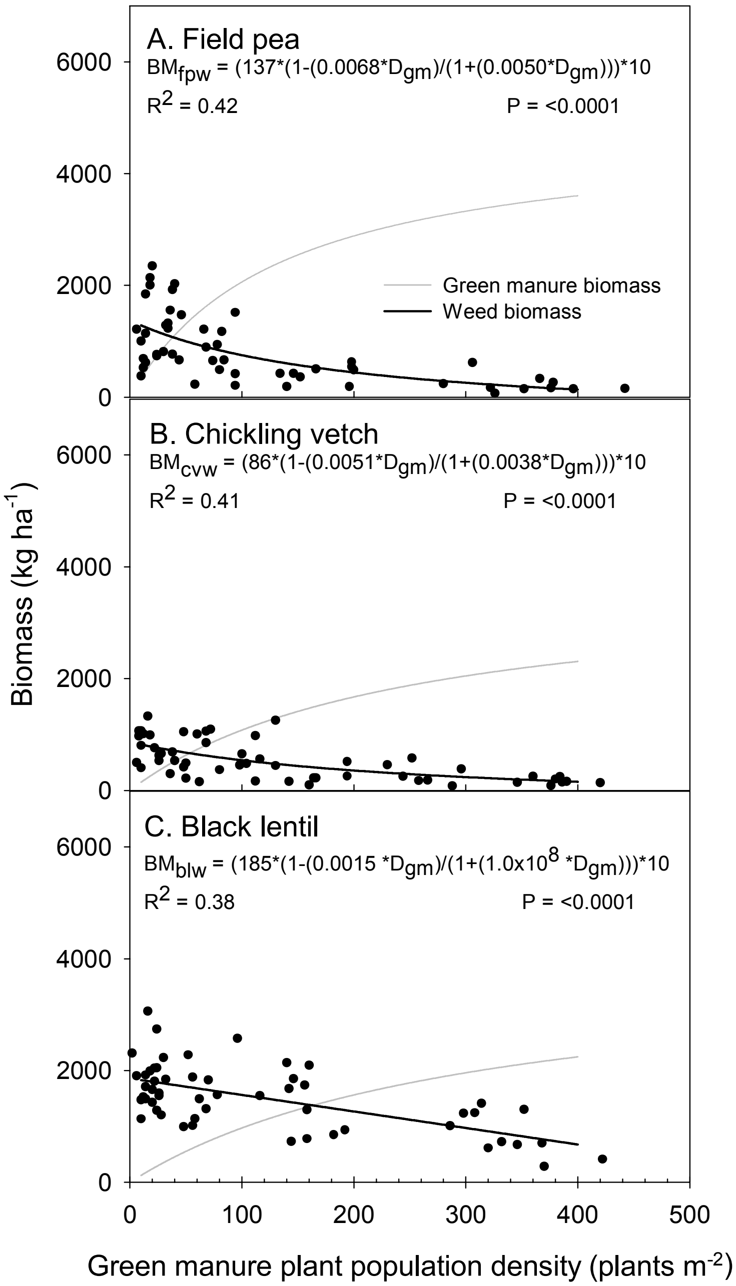

Figure 3.5: Effect of plant population density on weed biomass accumulation growing with (A) field pea, (B) chickling vetch, and (C) black lentil green manure crops at early bud. Curves are based on the equation $BM_w = (Y_{max} * (1 – (r_{max} * D_{gm}) / (1 + (y * D_{gm}))*10$, where BM_w is weed biomass in kg ha^{-1}, Y_{max} is the maximum potential weed biomass in kg ha^{-1} as crop density approaches zero, r_{max} is the slope of the change in weed biomass as green manure plant population density increases, y is the minimum weed biomass yield in kg ha^{-1} as crop density approaches infinity, and D_{gm} is the green manure plant density in plants m^{-2} (modified from Cousens, 1985). Ten is a conversion factor to convert from weed biomass in g m^{-1} to kg ha^{-1}.

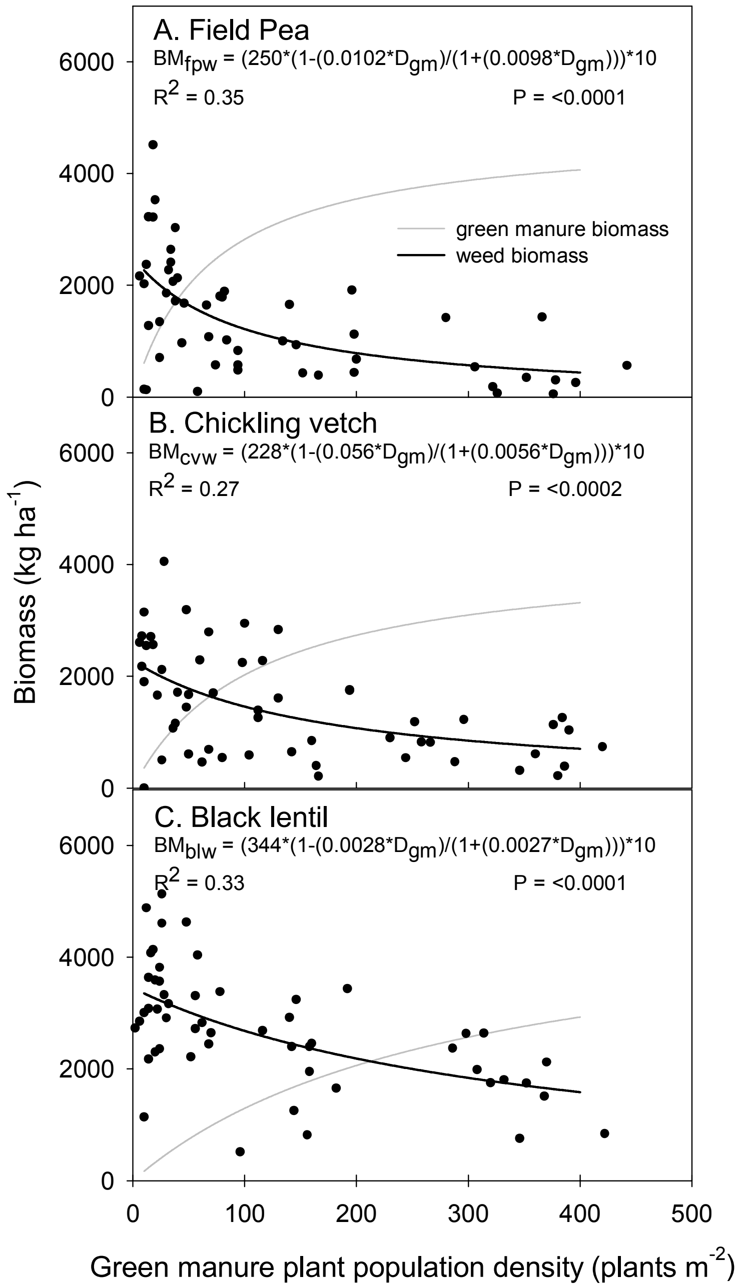

Figure 3.6:Effect of plant population density on weed biomass accumulation growing with (A) field pea, (B) chickling vetch, and (C) black lentil green manure crops at full bloom. Curves are based on the equation $BM_w = (Y_{max} * (1 - (r_{max} * D_{gm}) / (1 + (y * D_{gm}))*10$, where BM_w is weed biomass in kg ha^{-1}, Y_{max} is the maximum potential weed biomass in kg ha^{-1} as crop density approaches zero, r_{max} is the slope of the change in weed biomass as green manure plant population density increases, y is the minimum weed biomass yield in kg ha^{-1} as crop density approaches infinity, and D_{gm} is the green manure plant density in plants m^{-2} (modified from Cousens, 1985). Ten is a conversion factor to convert from weed biomass in g m^{-1} to kg ha^{-1}.

were higher for all species at full bloom than at early bud (Table 3.11). This reflects increases in weed biomass with time between the green manure crop early bud and full bloom stages. Among green manure species, trends for Y_{max} depended upon harvest stage. At early bud, the Y_{max} of chickling vetch was lower than black lentil, but did not differ from field pea (Table 3.11). The Y_{max} for black lentil at full bloom was significantly greater than both chickling vetch and field pea (Table 3.11). This suggests that chickling vetch and field pea have a better ability to suppress weeds than black lentil.

Biederbeck et al. (1993) found that feed pea had the lowest weed dry matter expressed as a percentage of total above ground biomass at the full bloom stage when compared to chickling vetch and black lentil. They reported weed dry matter as a percentage of total above ground plant dry matter to be 18% for feed pea, 31% for chickling vetch, and 31% for black lentil. Comparisons to this weed data are limited as weed control was practised and the authors cautioned about the representativeness of the data. However, the general trends of the Biederbeck et al. (1993) study agree with the results of this study in that that field pea had the lowest percent weed biomass at fully bloom of all three species. When comparing weed biomass production at equivalent plant densities, this study found chickling vetch had a lower percent weed biomass than black lentil (data not shown).

3.3.5 Effect of harvest date on crop and weed biomass

Green manure biomass production increased between the early bud and full bloom stages across all plant population densities for both weedy and weed-free treatments (Table 3.8) (Figure 3.1 to 3.4). This was reflected in higher values for W_m at the full bloom stage (Table 3.10). Weed biomass also increased between early bud and full bloom for all green manure species (Table 3.9) (Figure 3.5 and 3.6). This increase was reflected in higher values for Y_{max} at the full bloom stage (Table 3.11). The increase in weed biomass between the two harvest dates was greater than increases in crop biomass (Figure 3.5 and 3.6). For example, black lentil crop biomass increased by 25% between early bud and full bloom at density of 64 plants m^{-2}, while the biomass of weeds growing with black lentil at that density increased

Table 3.11: Estimates and standard errors of Y_{max}, $r_{max,}$ and y equation parameters for weed biomass at early bud and full bloom.

	Early bud		Full bloom	
Y_{max}^{a}	Estimate	Standard error	Estimate	Standard error
Field pea	137ab*	18.2	250b	42.7
Chickling vetch	86b	10.0	228b	33.0
Black lentil	185a	8.8	344a	27.1
r_{max}^{b}				
Field pea	0.0068	0.00412	0.0102	0.00758
Chickling vetch	0.0051	0.00302	0.0056	0.00470
Black lentil	0.0015	0.00023	0.0028	0.00219
y^{c}				
Field pea	0.0050	0.00503	0.0098	0.00971
Chickling vetch	0.0038	0.00403	0.0056	0.00713
Black lentil	$1.0x10^{-8}$	0.00000	0.0027	0.00436

[a] Y_{max} is the maximum potential weed biomass as crop density approaches zero

[b] r_{max} is the slope of the change in weed biomass as green manure plant population density increases

[c] Y is the minimum weed biomass yield as crop density approaches infinity

* Letters indicated significantly different estimates within columns for each parameter ($P = 0.05$)

by 42% between early bud and full bloom. This trend is consistent among all three crops and suggests that under weedy conditions, early incorporation of green manure crops resulted in a greater proportion of crop biomass relative to weed biomass.

A few studies have compared green manure crop biomass production between harvest stages. Brandt (1996) found the average biomass of black lentil to double from 1500 kg ha^{-1} to 3170 kg ha^{-1} from early bud to full bloom in the Dark Brown soil zone. A later study by Brandt (1999) also found the average biomass of black lentil to double from 1660 kg ha^{-1} to 3220 kg ha^{-1} from early bud to full bloom. Pikul et al. (1997) found the average dry weight of black lentil to increase from 1679 kg ha^{-1} to 5261 kg ha^{-1} between the full bloom stage and a later termination stage during pod set. In this study, doubling of green manure biomass was observed between early bud and full bloom for chickling vetch under both weedy and weed-free conditions. Biomass production for black lentil and field pea was only doubled between early bud and full bloom under weed-free conditions at plant population densities of less than 50 plants m^{-2} (Figures 3.1 to 3.4).

3.3.6 Effect of weed treatment on crop and weed biomass

Across all plant population densities, biomass production of green manure crops grown under weedy conditions was generally lower than when grown under weed-free conditions (Figures 3.1 to 3.4). Two exceptions occurred. The first was in chickling vetch at the early bud stage where biomass production across all plant population densities was the same between weed treatments (Table 3.8) (Figure 3.1 and 3.2). There was no difference between the W_m and a variables used to describe the biomass curves for chickling vetch under both weedy and weed-free treatments at early bud (Table 3.8 and 3.10). The second exception was in field pea at the early bud stage where weedy treatments at high plant population densities (300 to 400 plants m^{-2}) had higher crop biomass production than under weed-free conditions (Figure 3.1 and 3.2). This difference may be due to an influential data point in the weedy treatment occurring at a higher density (Figure 3.2 A). Although estimated biomass production of weedy treatments was unexpectedly higher than weed-free treatments, the W_m values did not differ between weedy and weed-free treatments (Table 3.8). Thus this difference may be of little biological significance.

When comparing the shape of biomass yield curves between weedy and weed-free treatments for all green manure species (Figure 3.1 and 3.3 vs. Figure 3.2 and 3.4), only the biomass accumulation of weed-free treatments approached a maximum at higher green manure plant population densities. Under weedy conditions green manure crop biomass for all three species continued to increase across all plant population densities, even up to 400 plants m^{-2}. This indicated that higher plant population densities were needed under weedy conditions to produce a given amount of green manure biomass.

Each green manure crop species responded differently to weed competition. This can be quantified in terms of the competitive effect of each species on weed biomass production and in their competitive response as indicated by green manure biomass production (Goldberg and Landa, 1991). Field pea and chickling vetch had a greater competitive effect of suppressing weed biomass compared to black lentil. This was indicated by the lower Y_{max} value for field pea and chickling vetch (Table 3.11). Chickling vetch had the greatest competitive response to weeds as it was able to tolerate weed competition. Chickling vetch was the only species whose W_m value for crop biomass did not significantly change between weedy and weed-free conditions (Table 3.10). Although Wall et al. (1988) and Wall and Campbell (1993) found chickling vetch to be a poor competitor with both weeds and volunteer cereals, this phenomenon could suggest that chickling vetch may possibly have an allelopathic effect on weed growth. As chickling vetch reached the early bud stage earlier than field pea and black lentil (Table 3.2), this phenomenon could also be due to the fact that weeds had less time to grow and accumulate biomass before chickling vetch reached the early bud and full bloom stages.

In the present experiment, competitive ability was determined by the ability of a plant to maximize its own biomass production while minimizing weed biomass production. Using this criteria, field pea was the most competitive species. Field pea usually had the highest value of W_m for crop biomass (Table 3.10) and a lower Y_{max} value for weed biomass (Table 3.11) when compared to the other two species.

Chickling vetch was able to achieve comparable weed suppression to field pea as indicated by their similar Y_{max} values for weed biomass (Table 3.11), but it did not produce as much biomass as field pea (Figure 3.5 and 3.6). Of the three species, black lentil was the poorest competitor with weeds. It had the poorest suppression of weeds, as reflected in its higher Y_{max} value for weed biomass at full bloom (Table 3.11) and lower W_m value for crop biomass at early bud (Table 3.10).

Harvest date influenced the relative competitive abilities of chickling vetch and black lentil. Under weedy conditions, chickling vetch and black lentil produce similar biomass at the same densities and similar W_m values when terminated at early bud (Figure 3.2 and Table 3.10). When left to compete with weeds until full bloom, chickling vetch produced more biomass than black lentil at the same densities (Figure 3.4). Chickling vetch also had a higher W_m value than black lentil at full bloom (Table 3.10). However, under weed-free conditions, yield differences between chickling vetch and black lentil between the early bud and full bloom stages were not observed (Figure 3.1 and 3.3) and there was no difference between their W_m values (Table 3.10).

3.3.7 Soil moisture

Few differences in soil moisture levels were observed in this experiment. Significant treatment effects were found at the 0 to 15 and 0 to 30cm depths (Table 3.12 and 3.13), but never at the 60 cm depth (data not shown). When analyzing soil moisture data from both sites combined, significant treatment effects were only observed at the 0 to 15cm depth. Although covariance tests indicated that there is no significant site effect when performing a combined analysis on data from both experiments, significant trends are present at the 0 to 30 cm depth when analyzing each experiment separately.

Table 3.12: Analysis of variance for volumetric soil moisture data at early bud for the 0 to 15 and 0 to 30 cm soil depths.

	0 to 15 cm				0 to 30 cm			
Kernen 2 Effect	Num[a] df	Den[b] df	F value[c]	P > F	Num df	Den df	F value	P > F
Weeds[d]	1	86	4.03	0.0363*	1	3	2.11	0.2475
Species[e]	2	86	0.68	0.2305	2	80	0.32	0.7254
weeds*species	2	86	2.61	0.0284*	2	80	0.52	0.5939
density[f]	4	86	0.34	0.0937	4	80	5.64	0.0005***
weeds*density	4	86	0.24	0.7868	4	80	2.36	0.0600
species *density	8	86	0.98	0.2250	8	80	0.77	0.6313
weeds*species*density	8	86	0.74	0.7004	8	80	0.41	0.9140
SPG Effect								
weeds	1	3	3.12	0.1752	1	3	4.6	0.1214
species	2	79	1.46	0.2380	2	84	1.09	0.3405
weeds*species	2	79	2.85	0.0638	2	84	1.05	0.3555
density	4	79	9.90	<0.0001*	4	84	6.19	0.0002***
weeds*density	4	79	1.32	0.2699	4	84	0.89	0.4733
species *density	8	79	1.08	0.3880	8	84	1.31	0.2502
weeds*species*density	8	79	0.43	0.8972	8	84	0.98	0.4611
Combined sites Effect								
weeds	1	4	10.2	0.0363*	1	5	2.09	0.2111
species	2	191	1.48	0.2305	2	191	0.66	0.5163
weeds*species	2	191	3.63	0.0284*	2	191	0.33	0.7229
density	4	4	4.33	0.0937	4	4	2.98	0.1579
weeds*density	4	191	0.43	0.7868	4	5	0.90	0.5265
species *density	8	191	1.34	0.2250	8	191	0.70	0.6908
weeds*species*density	8	191	0.69	0.7004	8	191	0.84	0.5642

[a] Numerator degrees of freedom
[b] Denominator degrees of freedom
[c] Calculated *F*-value
[d] Weed treatments: weedy and weed-free
[e] Green manure species: field pea, chickling vetch, and black lentil
[f] Green manure target plant population densities: 10, 24, 64, 160, 400 plants m^{-2}
* Significantly different ($P = 0.05$)
*** Significantly different ($P = 0.001$)

Table 3.13: Analysis of variance for volumetric soil moisture data at full bloom for the 0 to 15 and 0 to 30 cm soil depths.

	0 to 15 cm				0 to 30 cm			
Kernen 2 Effect	Num df	Den df	F value	P > F	Num df	Den df	F value	P > F
weeds [d]	1	83	0.31	0.5789	1	82	0.98	0.3247
species [e]	2	83	0.43	0.6501	2	82	0.97	0.3852
weeds*species	2	83	1.07	0.3460	2	82	0.69	0.5049
density [f]	4	83	1.93	0.1133	4	82	1.86	0.1261
weeds*density	4	83	1.02	0.4013	4	82	1.18	0.3237
species *density	8	83	1.08	0.3824	8	82	0.90	0.5174
weeds*species*density	8	83	0.48	0.8699	8	82	0.54	0.8213
SPG Effect								
weeds	1	6	1.14	0.3289	1	3	1.55	0.2985
species	2	77	2.25	0.1124	2	81	1.37	0.2604
weeds*species	2	77	1.03	0.3625	2	81	1.27	0.2874
density	4	77	0.59	0.6686	4	81	1.34	0.2639
weeds*density	4	77	1.28	0.2839	4	81	0.94	0.4452
species *density	8	77	1.80	0.0899	8	81	2.40	0.0221*
weeds*species*density	8	77	0.59	0.7823	8	81	0.53	0.8282
Combined sites Effect								
weeds	1	3	2.72	0.1984	1	6	2.09	0.2111
species	2	1	0.57	0.6825	2	13	0.66	0.5163
weeds*species	2	3	0.57	0.6181	2	170	0.33	0.7229
density	4	4	1.24	0.4230	4	9	2.98	0.1579
weeds*density	4	176	1.65	0.1636	4	6	0.90	0.5265
species *density	8	176	1.84	0.0726	8	13	0.70	0.6908
weeds*species*density	8	175	0.49	0.8609	8	170	0.84	0.5642

[a] Numerator degrees of freedom
[b] Denominator degrees of freedom
[c] Calculated *F*-value
[d] Weed treatments: weedy and weed-free
[e] Green manure species: field pea, chickling vetch, and black lentil
[f] Green manure target plant population densities: 10, 24, 64, 160, 400 plants m^{-2}
* Significantly different (*P* = 0.05)

3.3.7.1 Effect of green manure crop species

There were no differences in soil moisture among the three different green manure crop species at any soil depth (Table 3.12 and 3.13). This finding was unexpected as biomass production among green manure crops differed significantly and it was hypothesised that species producing more biomass would use more soil water because of higher transpiration. Biederbeck and Bouman (1994) also did not find significant differences in soil water use among black lentil, chickling vetch, and feed pea when grown as green manure crops. Rather, differences were found between green manure treatments, summer fallow, and continuous wheat production. Biederbeck and Bouman (1994) suggested that chickling vetch and feed pea had higher water use efficiencies because they produced more biomass using similar amounts of water when compared to black lentil and tangier flatpea. However, their water use efficiency calculation did not support their observation because of large experimental errors. Following the same reasoning, this study predicts that water use efficiency would be higher for field pea than chickling vetch or black lentil. However, since initial soil moisture measurements were not collected, it was not possible to calculate water use efficiency.

3.3.7.2 Effect of weed treatment

Weed treatment had a significant effect on soil moisture levels at the early bud stage (Table 3.12). Volumetric soil moisture was higher under weed-free conditions (8.16%) than under weedy conditions (7.09%) within the 15 cm depth at the early bud stage for both sites ($P = 0.0363$). This indicates that weeds growing with green manure crops used a significant amount of water within the surface layer of the soil profile by the early bud stage. Differences between weed treatments were no longer detectable at the full bloom stage for any depth at both sites, suggesting that demands on soil moisture were greater by the full bloom stage.

Among the three green manure species, black lentil extracted less soil moisture than the other two green manure species within the top 15 cm under weed-free conditions at the early bud stage at both sites (Figure 3.7). Of all three species,

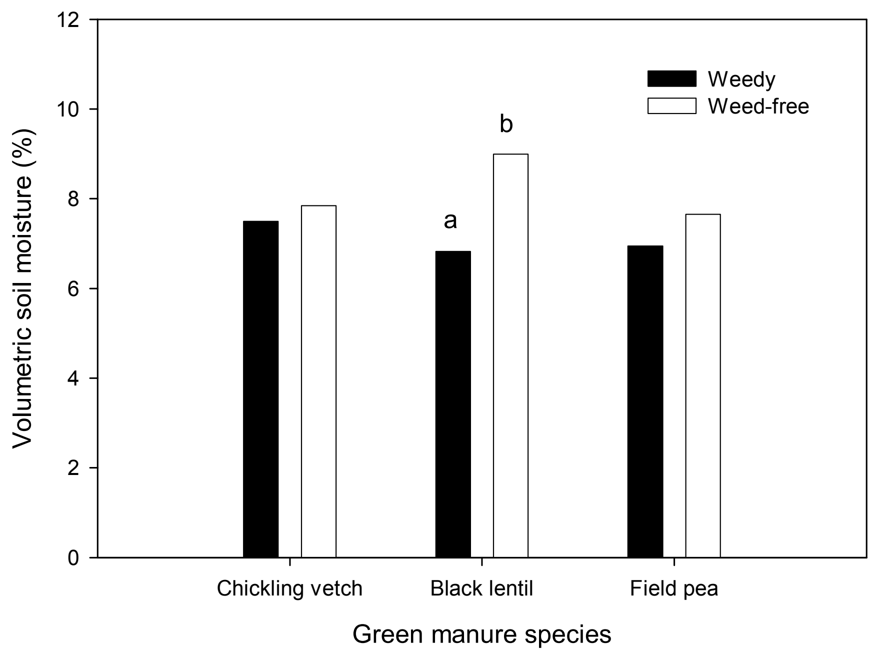

Figure 3.7: Effect of green manure species and weed treatment on soil moisture from 0 to 15 cm at early bud for both Kernen 2 and SPG locations combined. Letters indicate significant differences among weed treatments within species (P = 0.05).

black lentil crops had the highest soil moisture levels under weed-free conditions, but under weedy conditions it had the lowest levels at both sites. Under weedy conditions, black lentil is the least competitive species and had the highest amount of weed biomass production. Thus, the lower soil moisture level of black lentil under weedy conditions likely had more to do with its poor ability to compete with weeds rather than its own water use.

3.3.7.3 Effect of target plant population density

The effect of plant density on soil moisture levels at early bud became apparent when each location was analyzed separately for both the 0 to 15 and 0 to 30 cm soil depths (Table 3.12). At SPG, soil moisture levels decreased as target plant population density increased for the 0 to 15 cm depth over all species and weed treatments (Figure 3.8). Percent soil moisture doubled from 3.2% at 400 plants m^{-2} to 6.2% at 10 plants m^{-2}.

Currently recommended plant population densities for seed production of field pea are 60 to 90 plants m^{-2} and for black lentil are 80 to 130 plants m^{-2}. Recommended plant population densities for chickling vetch will be assumed to be 50 to 55 plants m^{-2} based on Biederbeck et al. (1993) and Bullied et al. (2002). Considering the highest densities from the range of recommended plant population densities, average soil moisture levels for 0 to 15 cm depth at the early bud stage averaged over all three species range from 4.0 to 4.7% (Figure 3.8). Increasing plant population densities to an extreme of 400 plants m^{-2} would decrease soil moisture levels by 1.0 to 1.5% in the 0 to15 cm depth at early bud. Thus, it is reasonable to recommend moderate increases in annual green manure plant population densities without causing excessive depletion of soil moisture reserves in the 0 to15cm depth.

Soil moisture at the 30 cm depth also decreased significantly as target plant population density increased at both the SPG and Kernen 2 sites (Figure 3.9). There were greater differences in soil moisture among plant population densities at Kernen 2 than at SPG. Percent soil moisture from 0 to 30 cm depth at early bud decreased from 28.8% at 10 plants m^{-2} to 19.7% at 400 plants m^{-2} at Kernen 2 and

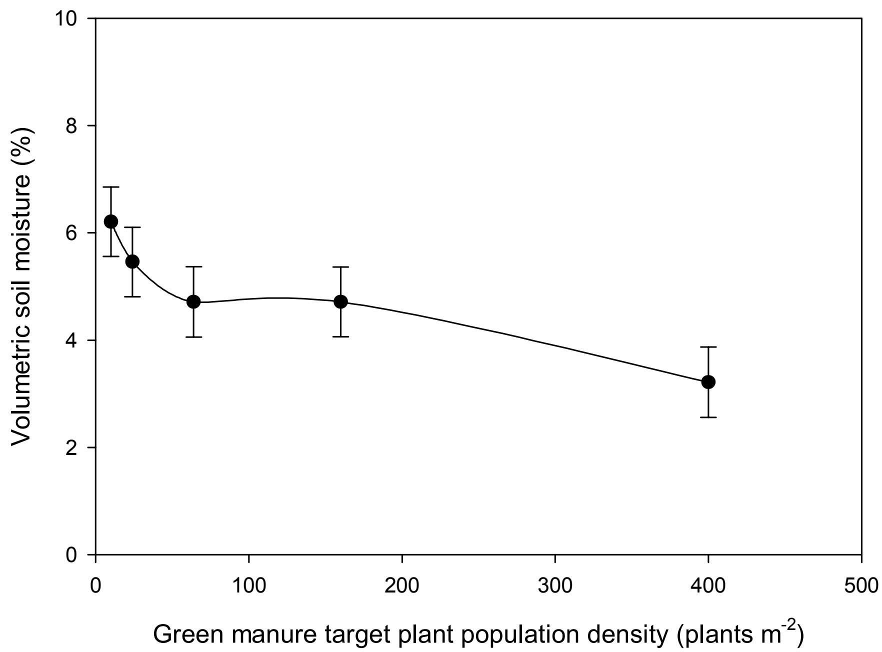

Figure 3.8: Effect of green manure target plant population density on soil moisture from 0 to15 cm averaged over all green manure species and weed treatments at early bud at SPG. Error bars represent one standard error of the mean.

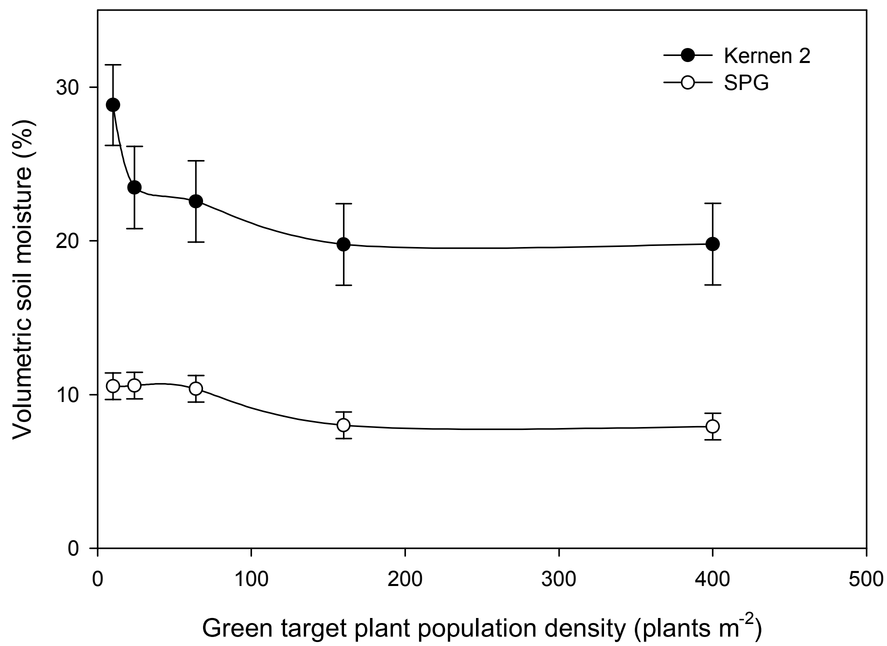

Figure 3.9: Effect of green manure target plant population density on soil moisture from 0 to 30 cm at early bud at Kernen 2 and SPG. Error bars represent one standard error of the mean.

from 10.5% at 10 plants m^{-2} to 7.9% at 400 plants m^{-2} at SPG (Figure 3.9). Considering the highest densities from the range of recommended plant population densities, average soil moisture levels for all three species range from 22.5 to 19.7% for Kernen 2 and 10.4 to 8.0% for SPG. Increasing plant population densities to an extreme of 400 plants m^{-2} would decrease soil moisture levels by 0 to 2.8% at Kernen 2 and by 0.1 to 2.5% at SPG in the 0 to 30 cm soil depth. This suggests that moderate increases in annual green manure plant population densities would not cause excessive depletion of soil moisture reserves in the 0 to 30 cm soil depth.

A weed by density interaction trend ($P = 0.1$) was seen at Kernen 2 for the 30 cm depth (Table 3.10). Differences in soil moisture between the weedy and weed-free treatments decreased as green manure crop target plant population density increased (Figure 3.10). As the total plant number increased, soil moisture reserves were exhausted in both weed treatments. Thus, greater differences in soil moisture between weed treatments existed at lower green manure plant population densities.

3.4 Summary

Green manure crop biomass increased with increasing plant population density while weed biomass decreased. Generally, green manure biomass production was higher under weed-free conditions than under weedy conditions. Thus, under weedy conditions it is necessary to increase green manure plant population densities to achieve comparable crop biomass production to weed-free conditions. Both green manure biomass and weed biomass increased between the early bud and full bloom stages. Proportional increases in weed biomass between the early bud and full bloom stages were greater for weed biomass than crop biomass. This suggests that earlier termination of green manure crops is necessary to increase the proportion of green manure crop biomass being incorporated. Although both green manure and weed biomass accumulate nitrogen, a greater proportion of green manure legume biomass will increase the amount of nitrogen in the cropping system trough nitrogen fixation.

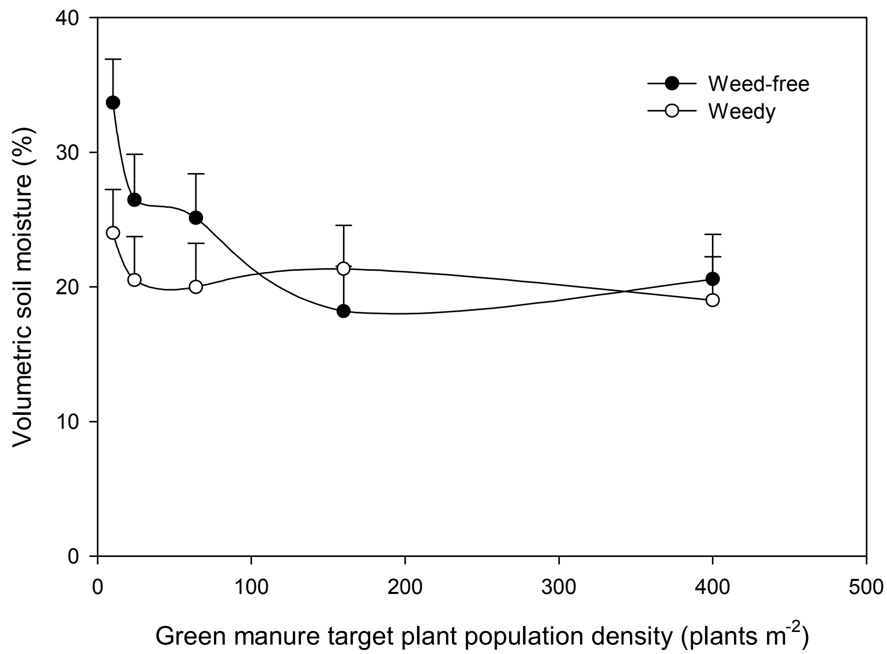

Figure 3.10: Effect of green manure target plant population density and weed treatment on soil moisture from 0 to 30 cm at early bud at Kernen 2. Error bars represent one standard error of the mean

Field pea was found to be the most competitive green manure crop under weedy conditions as it had the highest crop biomass production and the lowest weed biomass production. Chickling vetch also showed good suppression of weed biomass, but did not produce as much crop biomass as field pea. Black lentil was the least competitive green manure species as it had the lowest crop biomass production and the highest weed biomass production.

Fewer differences in soil moisture levels among green manure treatments were found than expected. No difference in soil moisture was found between the three green manure species tested. Soil moisture levels were found to decrease slightly with increasing green manure target plant population density at the 0 to15 cm and 0 to 30 cm soil depths. Decreases in soil moisture with increasing green manure target plant population density were only found at the 0 to 30 cm depth when each site was analyzed separately.

Results suggest that increasing green manure plant population densities would not excessively deplete soil moisture levels. Weed treatment influenced soil moisture levels, with lower soil moisture levels under weedy conditions. The results suggest that maintaining weed control during a green manure crop may be more critical to conserving soil moisture than green manure species selection or green manure target plant population density.

Given these results it is possible to compare the performance of the field pea, chickling vetch, and black lentil as annual green manure crops in terms of their biomass production, competitive ability with weeds, and soil moisture use. However, it is difficult to determine their relative contribution to a subsequent crop without considering their ability to accumulate nitrogen.

4.0 PLANT NITROGEN ANALYSIS

4.1 Introduction

Enhancing soil nitrogen availability is one of the major reasons for growing annual legume green manure crops (Biederbeck et al., 1993). As synthetic fertilizers are not used in organic cropping systems, green manure crops are an important source of nitrogen (Wallace, 2001). A recent survey of 46 organic farmers in Saskatchewan (Knight and Shirtliffe, 2003) found strong connections between the use of green manure crops and soil nitrogen levels. Of the 84 fields surveyed, the average soil nitrogen content of all fields reported deficient levels. Of the fields reporting marginal to optimum nitrogen levels 80% of producers reported using green manure crops within the past 5 years.

Annual green manure legumes can increase the amount of nitrogen in a cropping system through biological nitrogen fixation and can prevent losses of nitrogen through leaching and denitrification by acting as temporary nutrient storage units (Bremer and van Kessel, 1992a; Biederbeck et al., 1996). Upon incorporation of green manure crops, nitrogen in the plant tissue must mineralize to become available for uptake by cash crops the following spring.

The total nitrogen yield of green manure crop biomass will depend on the concentration of nitrogen in the biomass as well as the amount of biomass produced. Biederbeck et al. (1996) found the nitrogen concentration in the above ground portion of green manure crop biomass to range from 2.3% for feed pea to 2.6% for black lentil. Total nitrogen accumulation was highest for feed pea at 62 kg N ha^{-1}, followed by chickling vetch at 49 kg N ha^{-1}, and black lentil at 40 kg N ha^{-1}. Brandt (1999) also observed that the highest total nitrogen yield per unit area occurred where biomass production was maximized. Thus, plants with the capability of producing the most biomass may also accumulate the most nitrogen.

The objectives of this study were (1) to compare the concentration of nitrogen in the above ground biomass of field pea, chickling vetch, and black lentil when grown as green manure crops and (2) to determine if green manure crop species or green manure target plant population density influenced the accumulation of total nitrogen in above ground green manure biomass.

4.2 Materials and methods

Nitrogen analysis of green manure crop and weed biomass samples harvested at early bud was carried out using samples collected for the experiment in Chapter 3. Refer to the materials and methods section of Chapter 3.2 for complete details on site description, environmental conditions, experimental and treatment design, plot management, and biomass measurements.

Crop and weed samples were ground using a Wiley mill (Thomas Scientific, Swedesboro, NJ) to pass through a 2 mm screen. Samples were thoroughly mixed to ensure homogeneity. All samples from the 24, 160, and 400 plants m^{-2} target plant population densities were analysed using a Leco Corporation FP-528 Nitrogen Analyzer (Leco Corporation, St. Joseph, MI, USA) to determine the nitrogen concentration of the samples.

The total nitrogen content of crop, weeds, and total plot biomass were calculated by multiplying their nitrogen concentration by measured plot biomass yield. Total plot biomass was defined as the sum of crop and weed biomass for each plot. Nitrogen concentration for total plot biomass was back calculated using the calculated amount of plot nitrogen and the measured plot biomass yield. This data was analysed using the mixed procedure of SAS for all three locations combined (Littell et al., 1996). Site and blocks were considered random while weed treatment, green manure species, and green manure target plant population density were considered fixed. Analysis of data from all three experiments combined indicated no treatment by location covariance. Thus all data presented is the combined results from all three experiments.

4.3 Results

4.3.1 Nitrogen concentration

The nitrogen concentration of green manure crop biomass did not vary among the three green manure species (Table 4.1). Weed treatment had a small yet significant influence on the nitrogen concentration of green manure crop biomass with weed-free treatments having a higher nitrogen concentration than weedy treatments (Table 4.2). Green manure plant density also had a slight influence on nitrogen concentration of crop biomass with plants at lower target plant population densities having higher nitrogen concentrations (Table 4.1 and 4.2).

Few studies have quantified the nitrogen concentration of green manure crops. Zentner et al. (1996) found the nitrogen concentration of black lentil to be 2.76%, while Pikul et al. (1997) found it to be slightly lower at 2.13%. This is slightly lower than the nitrogen concentration of green manure biomass found in this study (Table 4.2).

Only green manure crop species influenced the nitrogen concentration of weed biomass (Table 4.3). The nitrogen concentration of weeds was lowest when grown with black lentil at 2.41% (Table 4.2) The nitrogen concentration of weeds did not differ significantly when grown with chickling vetch or field pea at 3.22 and 3.04 %, respectively (Table 4.2). Green manure target plant population density had no effect on the nitrogen concentration of weed biomass.

Differences in nitrogen concentration for total plot biomass were small yet significant (Table 4.2 and Table 4.4). A significant weed by density interaction indicated that the nitrogen concentration of all plot biomass in weed-free treatments was higher than in weedy treatments at low densities only (Figure 4.1). There was no change in nitrogen concentration of weedy treatments across green manure target plant population densities.

A weed by species interaction (Table 4.4) showed larger differences in nitrogen concentration of all plot biomass between weedy and weed-free treatments of black lentil crop biomass compared to chickling vetch or field pea (Figure 4.2).

Table 4.1: Analysis of variance for nitrogen concentration and total nitrogen content in crop biomass at early bud.

	Nitrogen concentration				Total nitrogen content			
Effect	Num df[a]	Den df[b]	F value[c]	P > F	Num df	Den df	F value	P > F
weeds[d]	1	4.62	7.29	0.0464*	1	5.53	4.69	0.0774
species[e]	2	3.86	2.09	0.2432	2	3.92	10.31	0.0275*
weeds*species	2	12.1	0.31	0.7357	2	5.9	1.7	0.2605
density[f]	2	4.02	8.94	0.0332*	2	10.1	119.3	<0.0001*
weeds*density	2	5.27	3.34	0.1155	2	7.5	0.33	0.7294
species *density	4	8	2.46	0.1294	4	11.5	1.55	0.2529
weeds*species*density	4	12	0.94	0.4758	4	136	6.15	0.0001*

[a] Numerator degrees of freedom
[b] Denominator degrees of freedom
[c] Calculated *F*-value
[d] Weed treatments: weedy and weed-free
[e] Green manure species: field pea, chickling vetch, and black lentil
[f] Green manure target plant population densities: 10, 24, 64, 160, 400 plants m^{-2}
* Significantly different ($P = 0.05$)

Table 4.2: Effect of green manure weed treatment, target plant population density, and species on average nitrogen concentration and total nitrogen content of green manure, weed, and total plot biomass at early bud.

	Nitrogen concentration			Total nitrogen content		
Weed treatments	Green manure	Weeds	Total plot	Green manure	Weeds	Total plot
		%			$kg\ ha^{-1}$	
Weedy	2.97	.	2.84	4.95	.	7.02
Weed-free	3.15	.	3.16	5.85	.	5.83
LSD (P=0.05)	0.18	.	0.31	1.04	.	0.70
Green manure target plant population density (plants m^{-2})						
24	3.26	2.71	3.12	2.57	3.36	4.26
160	3.01	2.97	2.97	5.92	1.72	6.79
400	2.92	3.04	2.90	7.70	1.12	8.24
LSD (P=0.05)	0.18	0.43	0.29	0.76	0.78	0.84
Green manure species						
Field pea	3.11	3.04	3.08	7.31	1.81	8.21
Chickling vetch	3.13	3.22	3.13	4.60	1.25	5.23
Black lentil	2.94	2.41	2.80	4.28	3.14	5.85
LSD (P=0.05)	0.29	0.39	0.31	2.05	0.45	2.10

Table 4.3: Analysis of variance for nitrogen concentration and total nitrogen content in weed biomass at early bud.

	Nitrogen concentration				Total nitrogen content			
Effect	Num df[a]	Den df[b]	F value[c]	Pr>F	Num df	Den df	F value	Pr>F
species[d]	2	3.84	18.93	0.0102*	2	75.9	37.36	<0.0001*
density[e]	2	3.91	2.48	0.2011	2	4.29	32.88	0.0025*
species*density	4	68.1	1.54	0.1999	4	75.7	2.58	0.0439*

[a] Numerator degrees of freedom
[b] Denominator degrees of freedom
[c] Calculated *F*-value
[d] Green manure species: field pea, chickling vetch, and black lentil
[e] Green manure target plant population densities: 10, 24, 64, 160, 400 plants m^{-2}
* Significantly different ($P = 0.05$)

Table 4.4: Analysis of variance for nitrogen concentration and total nitrogen content in total plot biomass at early bud.

Effect	Nitrogen concentration				Total nitrogen content			
	Num[a] df	Den[b] df	F value[c]	Pr>F	Num df	Den df	F value	Pr>F
weeds[d]	1	4.31	14.55	0.0165*	1	6.92	10	0.0161*
species[e]	2	3.88	5.11	0.0817	2	3.9	8.8	0.0359*
weeds*species	2	145	5.35	0.0057*	2	138	3.71	0.027*
density[f]	2	3.94	2.44	0.2044	2	10.1	57.6	<0.0001*
weeds*density	2	145	17.26	<0.0001*	2	8.97	5.13	0.0359*
species *density	4	8.15	3.91	0.0467*	4	11.6	0.66	0.629
weeds*species*density	4	145	1.47	0.2131	4	138	4.65	0.0015*

[a] Numerator degrees of freedom
[b] Denominator degrees of freedom
[c] Calculated *F*-value
[d] Weed treatments: weedy and weed-free
[e] Green manure species: field pea, chickling vetch, and black lentil
[f] Green manure target plant population densities: 10, 24, 64, 160, 400 plants m^{-2}
* Significantly different ($P = 0.05$)

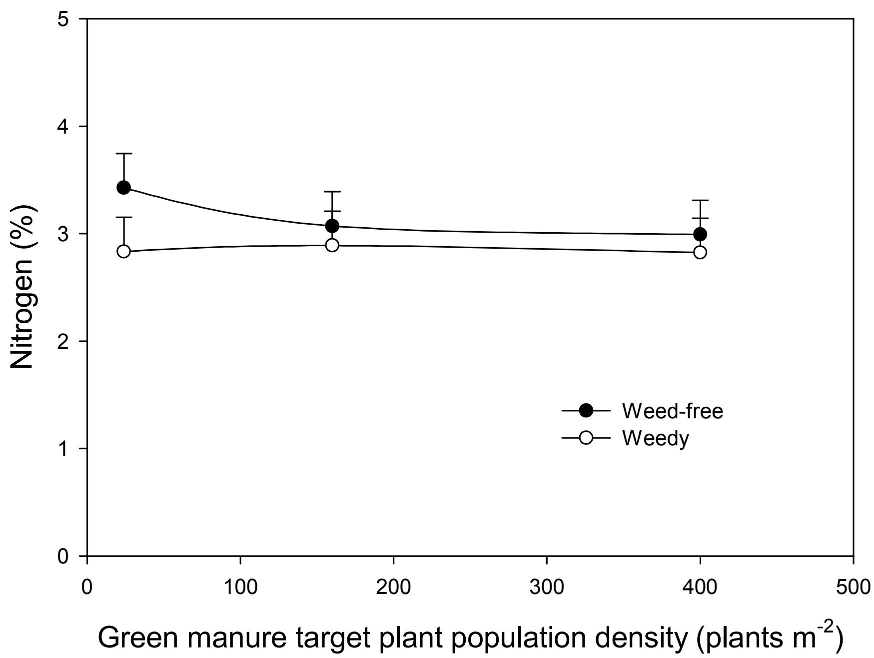

Figure 4.1: Effect of green manure target plant population density and weed treatment on nitrogen concentration of total plot biomass at early bud. Error bars represent one standard error of the mean.

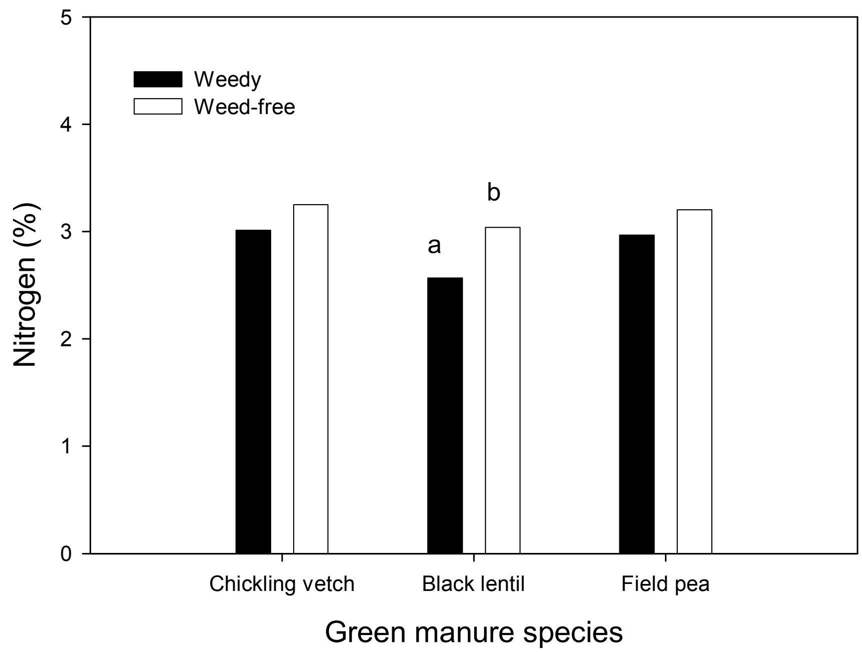

Figure 4.2: Effect of green manure species and weed treatment on the nitrogen concentration of total plot biomass at early bud. Letters indicate significant differences among weed treatments within species (*P* = 0.05).

This trend is similar to the trend seen for soil moisture levels (Chapter 3.3.7), however nitrogen concentration is always lower for both weedy and weed-free conditions when compared to field pea or chickling vetch. Of the main effects involved in this interaction, only weed treatment significantly influenced percent nitrogen of all plot biomass. Weed-free treatments had a nitrogen concentration of 3.16% compared to weedy treatments at 2.84% (P=0.0165). Thus, in terms of nitrogen concentration, there was no large advantage to growing a weed-free green manure crop.

A weak species by density interaction showed that chickling vetch was the only species that decreased in nitrogen concentration as density increased (Figure 4.3). The nitrogen concentration of field pea and black lentil was the same across all target plant population densities.

4.3.2 Total nitrogen

As there were no differences in nitrogen concentration among green manure species (Table 4.1), differences in total nitrogen among species was greatly influenced by their ability to produce biomass (Chapter 3). Average total nitrogen levels were highest for field pea, followed by chickling vetch and black lentil (Table 4.2). As biomass production among all green manure species increased with increasing target plant population density, total nitrogen in green manure crop biomass also increased (Table 4.2). Although a weed by species by density interaction occurred for total nitrogen in green manure crop biomass, no biological meaning could be found (data not shown).

Green manure treatments influenced total nitrogen in weed biomass (Table 4.3). Increasing green manure target plant population density decreased total nitrogen in weed biomass (Table 4.2 and 4.3). The total nitrogen in weeds growing with chickling vetch and black lentil declined consistently but not for weeds growing with field pea (Figure 4.4). Weeds growing with both chickling vetch and field pea had the same amount of nitrogen when the green manure crops were grown at 160 plants m^{-2} (Table 4.2, Figure 4.4). Just as weed biomass production was highest for

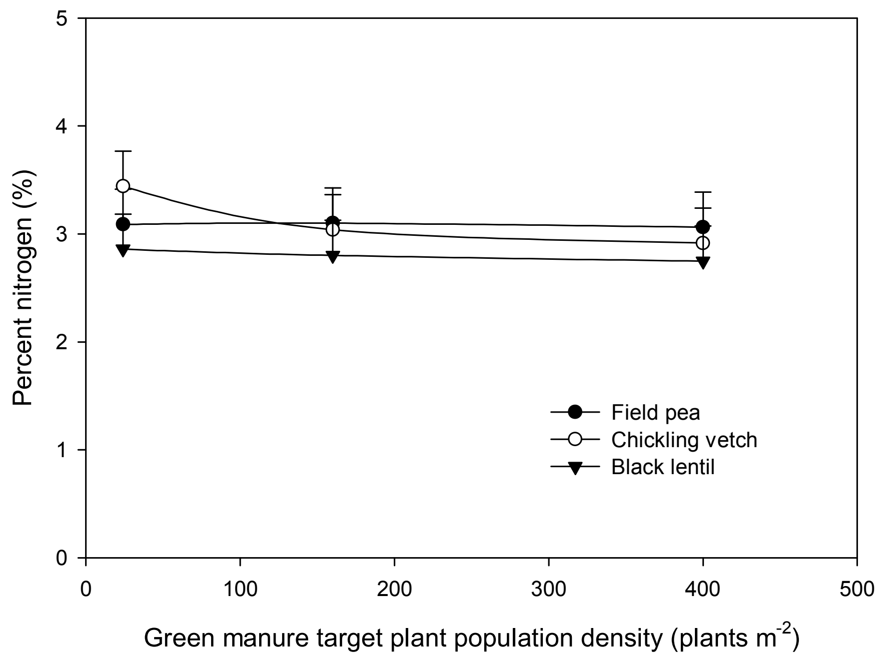

Figure 4.3: Effect of green manure target plant population density and species on the nitrogen concentration in all crop biomass at early bud. Error bars represent one standard error of the mean.

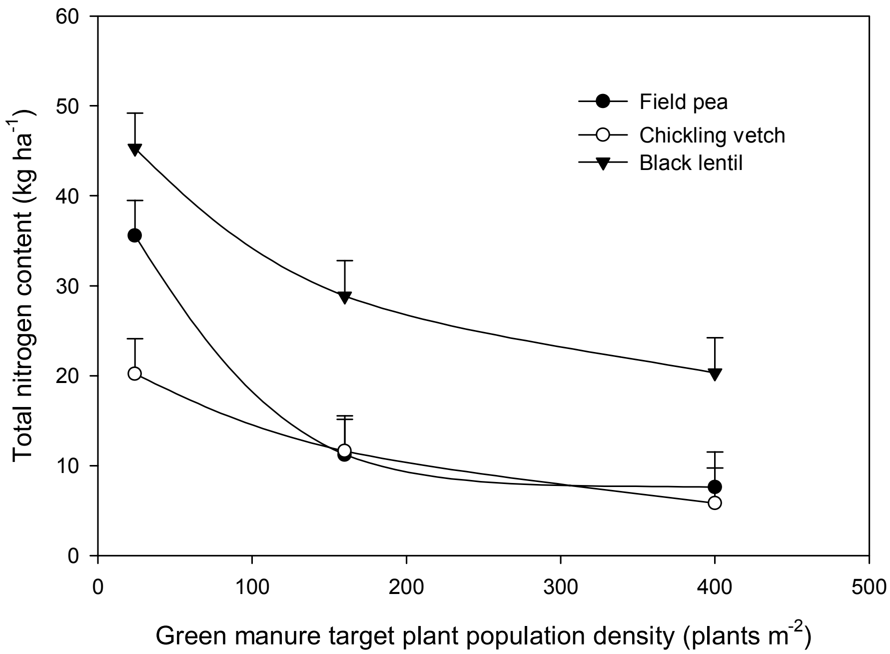

Figure 4.4: Effect of green manure target plant population density and species on total nitrogen in weed biomass at early bud. Error bars represent one standard error of the mean.

black lentil, so too was total nitrogen accumulation in weed biomass (Table 4.2). Thus, weeds growing with black lentil accumulated the highest amount of total nitrogen but had the lowest percent nitrogen (Table 4.2).

Greater differences in total nitrogen in total plot biomass were observed (Table 4.4). A weed by density interaction revealed total nitrogen in weed-free biomass was always less than total nitrogen in weedy biomass across all target plant population densities; however, the difference diminished as target plant population densities increased (Figure 4.5). A weed by species interaction indicated greater differences in total nitrogen between weedy and weed-free treatments of black lentil than for field pea or chickling vetch (Figure 4.6). The weed by species by density interaction revealed differences in total nitrogen accumulation among species as target plant population density increased for both weed treatments (Figure 4.7). Under weed-free conditions, maximums for total nitrogen accumulation of black lentil were reached above 200 plants m^{-2} and around 160 plants m^{-2} for field pea, but total nitrogen values for chickling vetch continuously increased (Figure 4.7 B). Under weedy conditions, total nitrogen values for field pea continuously increased but black lentil reached a maximum below 160 plants m^{-2} and chickling vetch at 160 plants m^{-2} (Figure 4.7 A).

4.3.3 Relative contributions of weed and green manure biomass

The proportional contribution of nitrogen from crop and weed biomass varied between green manure species (Figure 4.8). Nitrogen from crop biomass made a greater contribution to the nitrogen in total plot biomass for field pea and chickling vetch. Weed biomass made a relatively larger nitrogen contribution to total plot nitrogen for black lentil than for chickling vetch or field pea. For all species, the relative nitrogen contribution of weed biomass was greater at low densities (Figure 4.8).

The question can then be asked, does it matter if total plot nitrogen is accumulated through crop or weed biomass? As there was relatively little difference between the nitrogen concentration of weed biomass and crop biomass for the three green manure species, the critical factor was their ability to produce biomass. In this

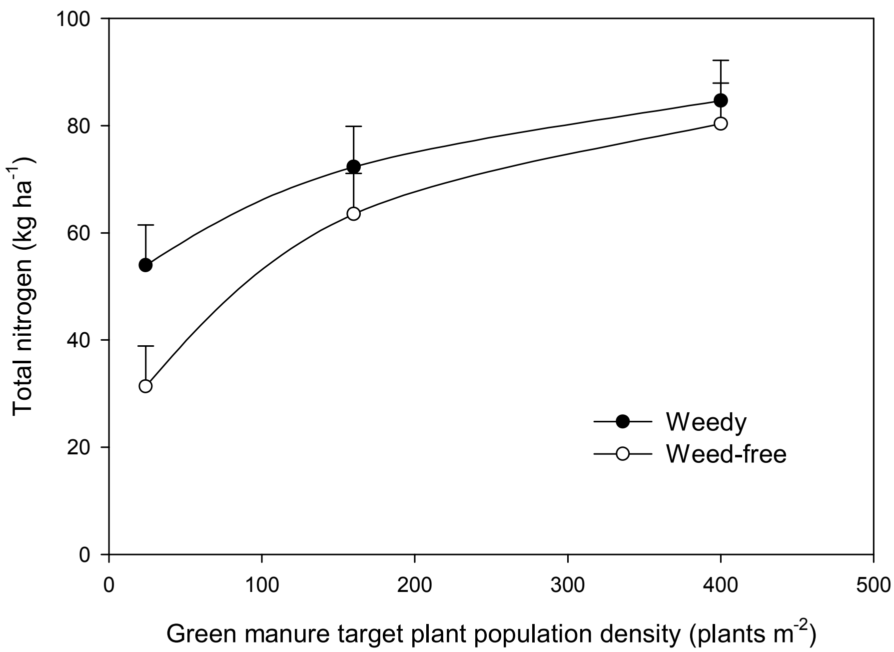

Figure 4.5: Effect of green manure target plant population density and weed treatment on total nitrogen in total plot biomass at early bud. Error bars represent one standard error of the mean.

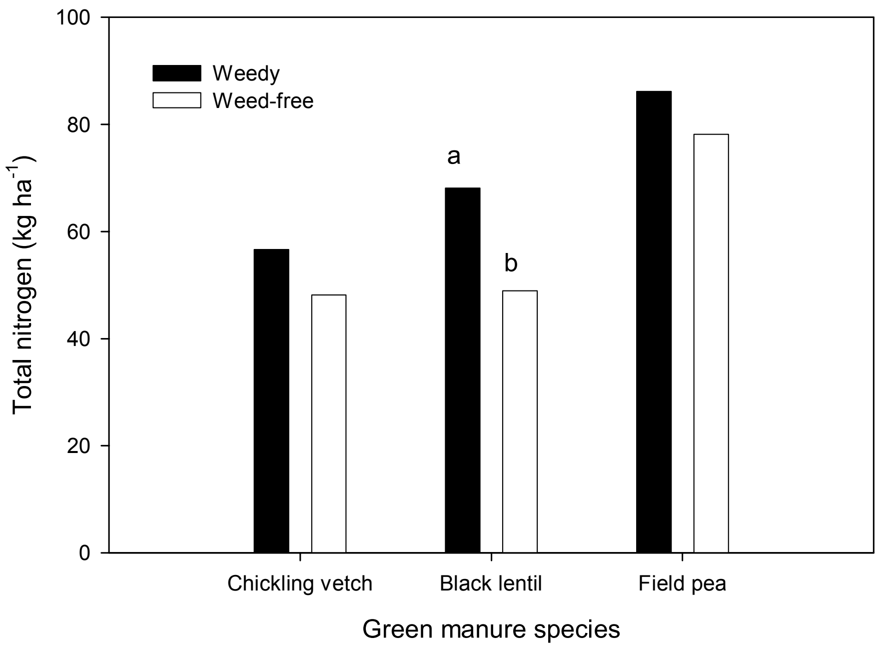

Figure 4.6: Effect of green manure species and weed treatment on total nitrogen in total plot biomass at early bud. Letters indicate significant differences between weed treatments within species ($P = 0.05$).

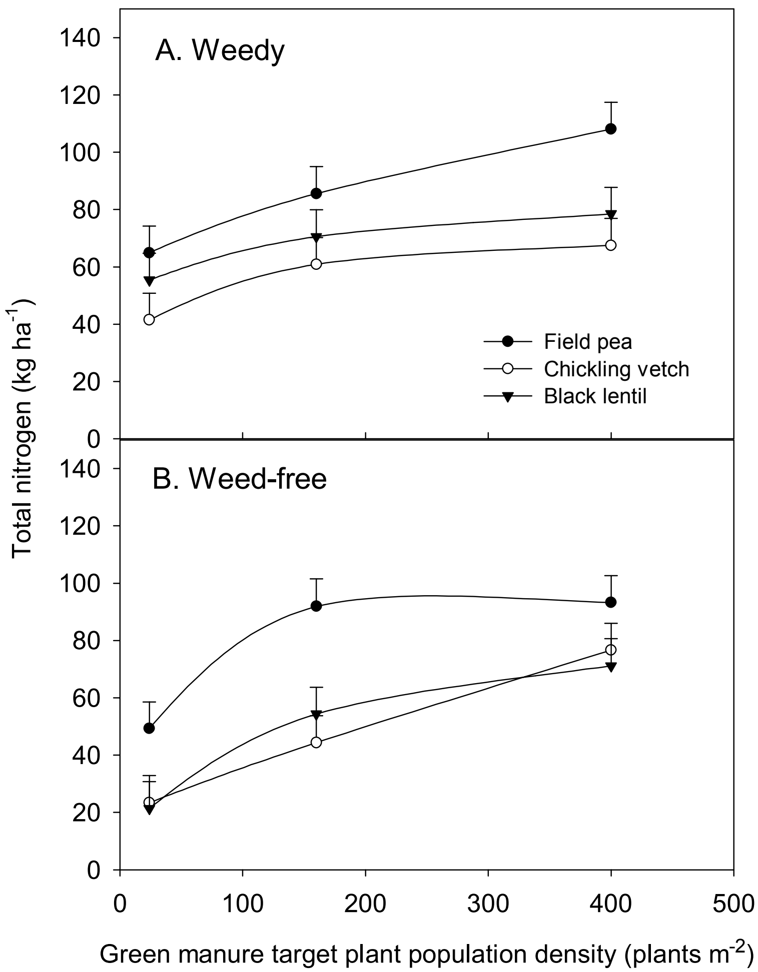

Figure 4.7: Effect of green manure target plant population density, weed treatment, and species on total nitrogen in total plot biomass at early bud. Error bars represent one standard error of the mean.

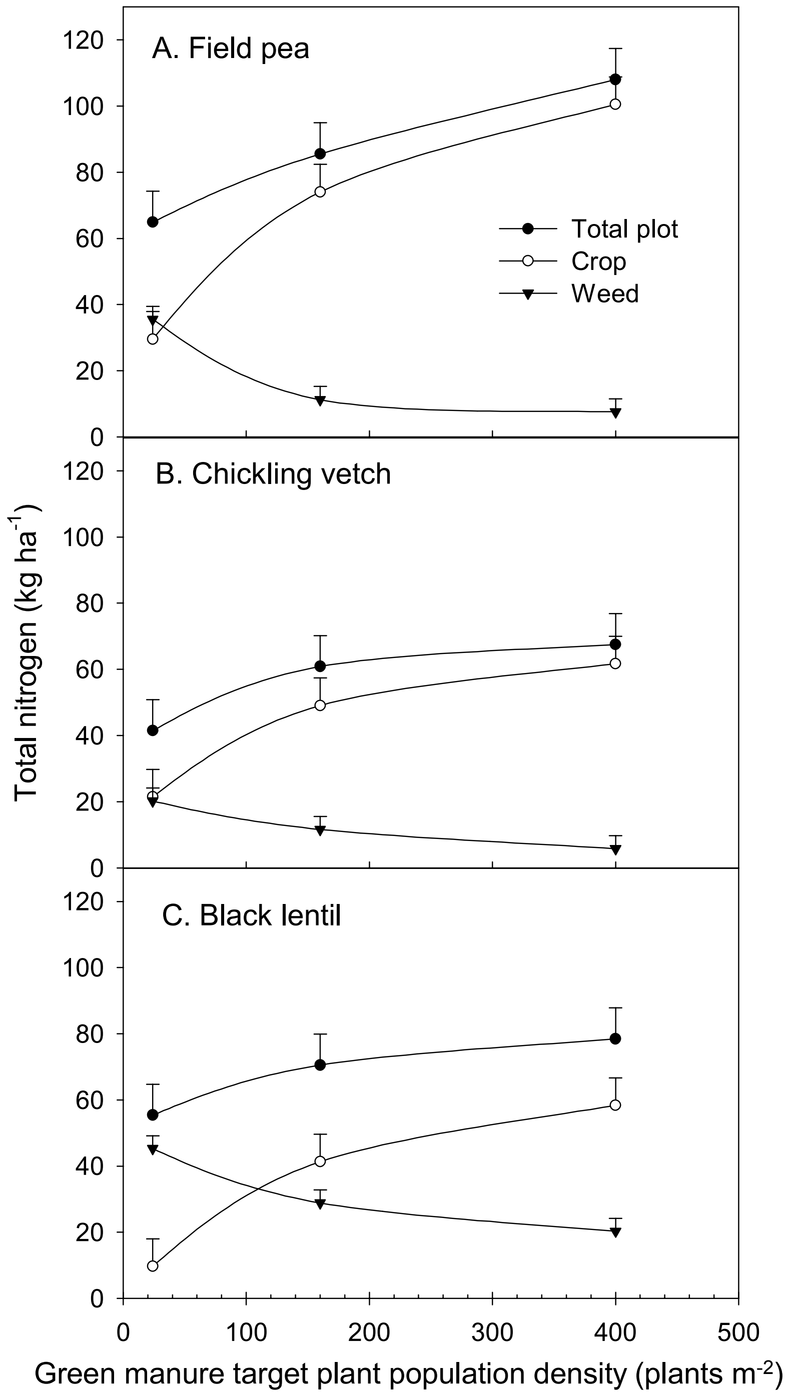

Figure 4.8: Effect of green manure target plant population density and species on total nitrogen in total plot biomass, green manure crop biomass, and weed biomass for (A) field pea, (B) chickling vetch, and (C) black lentil under weedy conditions at early bud. Error bars represent one standard error of the mean.

experiment the highest levels of biomass accumulation occurred when the most competitive green manure crop, field pea, was grown at high densities (Chapter 3). Although weed biomass made a significant contribution to total plot biomass of black lentil (Chapter 3), the total plot accumulation of total nitrogen in field pea (Figure 4.8 A) still surpassed black lentil (Figure 4.8 C).

Thus, the preference for accumulating nitrogen from green manure crop biomass depends on their maximum potential to produce biomass and their relative competitive ability. In the case of field pea with a high potential to produce biomass, the weeds may just limit its ability to accumulate biomass and nitrogen by depleting resources such as nitrogen and soil moisture. This may be especially critical in the early stages of crop development before the legume green manure crops are actively fixing nitrogen. In the case of black lentil, with its lower potential to produce biomass and its relatively poor ability to compete with weeds, weed biomass was able to make a significant contribution to total nitrogen production.

4.4 Summary

Nitrogen analysis revealed no difference between the nitrogen concentration of field pea, chickling vetch, or black lentil biomass. Also, little difference was found between the nitrogen concentration of the three green manure species and the weeds growing with them. Although nitrogen fixation was not measured in this experiment, these finding do not suggest that any one of these three species has a superior ability to fix nitrogen.

The total nitrogen accumulation of green manure crop biomass, weed biomass, and total plot biomass did vary between green manure species, weed treatments, and across target plant population densities. These differences were mostly due to changes in biomass production. Thus, maximizing biomass production was found to be the most important factor to increase soil nitrogen availability using green manure crops. Field pea produced the most crop biomass and accumulated the most total nitrogen among all three species. Black lentil accumulated comparable amounts of total nitrogen to chickling vetch.

In this experiment, the nitrogen concentration of weed biomass was close to that of the three annual legume green manure crops. This suggests that weeds growing with green manure crops would not limit the amount of nitrogen incorporated into the soil in a green manure system. However this experiment also found that maximum nitrogen accumulation was directly related to maximizing biomass accumulation. If a green manure crop has a greater potential to produce biomass than the weed community growing with it, then the nitrogen contribution of that green manure crop may be compromised by weedy conditions.

Given these results, it is possible to estimate and compare the relative nitrogen contribution of the field pea, chickling vetch, and black lentil as annual green manure crops to a subsequent crop. Plant population density recommendations could be determined by maximizing nitrogen accumulation for each species. However, as in the case with biomass production, nitrogen accumulation was not found to level off at high densities for any of the three green manure species under either weedy or weed-free conditions. The only exception was field pea under weed-free conditions. An arbitrary decision would have to be made as to how much nitrogen would be a sufficient contribution to subsequent crops. As well, the cost to produce nitrogen among each species differs depending upon their seed cost and ability to accumulate nitrogen. Thus, economic analysis would be useful in determining the value of nitrogen accumulated by green manure crops compared to their relative seed costs.

5.0 OPTIMUM PLANT POPULATION DENSITIES FOR THREE ANNUAL LEGUME GREEN MANURE CROPS

5.1 Introduction

Green manure crops produce different amounts of biomass (Chapter 3), accumulate different amounts of nitrogen (Chapter 4), and have different seed costs. Thus, differential costs exist to produce equivalent amounts of biomass or to accumulate equivalent amounts of nitrogen. Optimum plant population density recommendations are a trade-off between maximizing the value of crop yield and minimizing seed costs (Mohler, 2001). Several recent studies determine optimal plant population densities for large seeded pulse crops based on economic criteria (French et al., 1994; Jettner et al., 1999; Seymour et al., 2002; and Shirtliffe and Johnston, 2002). All experiments involved determining the yield-density relationship of the crop by growing it at a range of plant population densities and quantifying yield. In these studies, all legume crops had asymptotic yield-density responses and were valued in terms of seed production.

Determining optimum plant population densities for green manure crops is more difficult than for crops grown for seed or fodder, as they do not have direct economic value. In such a case, the value of their benefit to subsequent crops must be considered. The nitrogen contribution of green manure biomass is a means of measuring their contribution to the yield of a subsequent crop. The soil nitrogen content of organically managed fields in Saskatchewan is typically low (Knight and Shirtliffe, 2003). Under organic conditions it is not possible to use synthetic fertilizer to quickly resolve fertility problems. Thus, nitrogen from green manure crops is of great value in organic cropping systems. This value is most appropriately measured in terms of its contribution to the yield increase of a subsequent crop.

Studies have quantified the contribution of green manure nitrogen to subsequent wheat crops (Ladd et al., 1983; Ladd and Amato, 1986, Janzen et al., 1990; Bremer and van Kessel, 1992b). Green manure biomass labeled with ^{15}N has been used to follow the uptake of green manure nitrogen in a subsequent wheat crop or to quantify the mineralization of green manure nitrogen into available soil nitrogen for crop uptake. In Australia, Ladd et al. (1983) found 20 to 27% of annual legume green manure nitrogen in the above ground biomass of a subsequent wheat crop. Ladd and Amato (1986) found 17% of annual legume green manure nitrogen in the "tops" of the first subsequent wheat crop. In western Canada, Janzen et al. (1990) found average uptake of annual legume green manure nitrogen into the above ground biomass of a subsequent wheat crop to be 17%. Bremer and van Kessel (1992a) found 37% of annual legume green manure nitrogen to be mineralized by the end of the growing season of a subsequent crop in Saskatchewan. Under ideal conditions, all mineralized nitrogen could potentially be taken up by a subsequent crop.

The objective of this study was to use marginal cost analysis to generate the necessary economic guidelines to determine optimum plant population density recommendations for field pea (*Pisum sativum* L. cv. Trapper), chickling vetch (*Lathyrus sativus* L. cv. AC Green Fix), and black lentil (*Lens culinaris* Medikus cv. Indianhead) when grown as annual green manure crops. Marginal cost analysis was based on the contribution of nitrogen from green manure crops to the yield of a subsequent wheat crop.

5.2 Materials and methods

Marginal cost analysis (eg. Browning and Zupan, 1999) was used to determine the plant population density at which the change in seed cost to grow one more green manure plant per unit area is equal to the change in value of the yield of a subsequent wheat crop per unit area. The method used in this analysis was adapted from French et al. (1994) and Shirtliffe and Johnson (2002) to account for the value of a subsequent crop. The following analysis is based on empirical data from

Chapters 3 and Chapter 4, as well as on necessary assumptions to complete the model (Table 5.1). In order to isolate the comparative value of each green manure species relative to their seed cost, the model only considers nitrogen accumulated in green manure crop biomass and not from weed biomass.

5.2.1 Percent and total nitrogen

The amount of total nitrogen in above ground green manure biomass was calculated using the nitrogen concentration of green manure crops grown at 24, 160, and 400 plants m^{-2} when terminated at the early bud stage as reported in Chapter 4. Because the nitrogen concentration of green manure biomass decreased slightly with increasing green manure plant population density, least squares regression was used to determine the nitrogen concentration of green manure crop biomass from 24 to 400 plants m^{-2}. Separate regressions were used for weedy and weed-free treatments and were described by the equations:

$$PN_w = -0.0006D_{gm} + 3.0966 \quad [5.1]$$

$$PN_{wf} = -0.0011D_{gm} + 3.3659 \quad [5.2]$$

where PN is the nitrogen concentration of green manure crop biomass in % and D_{gm} is green manure plant population density in plants m^{-2}. The coefficients of determination (R^2) for weedy and weed-free regression equations were 0.94 and 0.75, respectively. Nitrogen concentration was averaged over all three green manure species as there was no significant difference in nitrogen concentration among species (Table 4.1). Nitrogen concentration was then multiplied by green manure biomass as estimated by equation 3.2 (Chapter 3): Thus, total nitrogen of green manure crop biomass was calculated using the equation:

$$TN_{gm} = PN * BM_{gm} \quad [5.4]$$

where TN_{gm} is total nitrogen in kg ha^{-1}, PN is percent nitrogen in %, and BM_{gm} is green manure biomass in kg ha^{-1}.

Table 5.1: Summary of model assumptions for marginal cost analysis of optimum plant population densities for three annual green manure legumes.

Assumption	Value	Source
Nitrogen mineralized from annual legume green manure crops in the first year	20 – 40%	Ladd et al., 1983; Ladd and Amato, 1986; Janzen et al., 1990; Bremer and van Kessel, 1992b
Wheat yield response to nitrogen fertilizer.		McKenzie et al, 1997; Alberta Agriculture, 2001
Average soil nitrogen level for organic farms in Saskatchewan	19.17 kg ha^{-1}	Knight and Shirtliffe, 2003
Average price for organic No. 1 Red Spring wheat	\$0.32 kg^{-1}	Saskatchewan Research Council, 2003
Seed costs in 2003 for: Trapper field pea; Indianhead black lentil; AC Green Fix chickling vetch	\$0.48 kg^{-1}; \$0.66 kg^{-1}; \$0.70 kg^{-1}	Wagon Wheel Seeds of Churchbridge, SK; Gary Meier Core Farm of Ridgedale, SK; Johnson Seeds of Arborg, MB, personal communication, 2004

5.2.2 Nitrogen mineralization

Based on the findings of Janzen et al. (1990) and Bremer and van Kessel (1992b), it was estimated that 20 to 40% of the nitrogen found in green manure biomass could be taken up by a subsequent wheat crop during the first growing season following green manure incorporation. The contribution of green manure nitrogen to a subsequent wheat crop (*MN*) in kg ha^{-1} was then calculated assuming 20% mineralization or 40% mineralization using the equations:

$$MN_{20} = TN_{gm} * 0.20 \qquad [5.4]$$

$$MN_{40} = TN_{gm} * 0.40 \qquad [5.5]$$

5.2.3 Wheat yield response to nitrogen

The yield response of a subsequent wheat crop to mineralized nitrogen from an annual legume green manure crops was estimated using wheat yield response curves to nitrogen fertilizer as determined by the equation:

$$Y = \frac{[YA * N_s]}{[YB0 + (YB1 * N_s) - (YB2 * (N_s * TAM)) + (YB3 * (N_s * (TAM)^2))]} \qquad [5.6]$$

where *Y* is yield of non irrigated CWRS wheat in kg ha^{-1}, N_s is total plant available nitrogen in kg ha^{-1}, and *TAM* is total available soil moisture in mm (McKenzie et al., 1997; Alberta Agriculture, 2001). Values of equation coefficients *YA*, *YB0, YB1, YB2,* and *YB3* were used for the Dark Brown soil zone and can be found in Table 5.2 (McKenzie et al., 1997; Alberta Agriculture, 2001).

Table 5.2: Equation coefficients used to calculate the yield response of non irrigated CWRS wheat to nitrogen amendments.

Coefficients	Values
YA	1000.0000000
YB0	16.6700000
YB1	0.5488300
YB2	0.0014000
YB3	0.0000015

Ns was determined using the equation:

$$N_s = S_n + MN \qquad [5.7]$$

where S_n is the soil test nitrate level to a depth of 60 cm in kg ha^{-1} and *MN* is the rate of nitrogen amendment to be added in kg ha^{-1}. S_n was assumed to be 19 kg ha^{-1}, the average soil nitrogen level on organic farms in Saskatchewan (Knight and Shirtliffe, 2003). Both MN_{20} and MN_{40} were used to calculate a high and low value of N_s.

TAM was estimated for the Dark Brown soil zone based on probability of precipitation using the equation:

$$TAM = PB0(_{dk\ brown}) - [PB1(_{dk\ brown}) * \%Prob] + ASML_{(fine)} \qquad [5.8]$$

where *PB0* and *PB1* are probability coefficients for May-June precipitation in the Dark Brown soil zone, *%Prob* is the percent probability for average precipitation, and *ASML* is the assumed available soil moisture level for fine textured soils in mm. The values for coefficients *PB0* and *PB1* were 247.08 and 1.61, respectively. The *%Prob* was 50%. The value of *ASML* was 30 mm.

5.2.4 Value of wheat yield increase

The value of wheat yield increases were calculated over all green manure plant population densities using the equation:

$$R_w = (Y_i - Y_o) * P_w \qquad [5.9]$$

where R_w is the value of wheat yield increase in \$, Y_i is the yield of wheat with nitrogen amendment in kg ha^{-1}, Y_o is yield of wheat without nitrogen amendment in kg ha^{-1}, and P_w is the average price in \$ kg^{-1} for certified organic No. 1 Red Spring wheat as determined by a 2002/2003 survey of selling prices received by organic farmers in Saskatchewan (Saskatchewan Research Council 2003). Based on the survey, No. 1 Red Spring wheat with 13.0 to 13.9% protein was the class of wheat sold in the largest quantity for an average price of \$0.32 kg^{-1} or \$8.75 bushel^{-1}.

5.2.5 Green manure seed cost

Commercial prices for certified seed in 2003 were used to calculate seed costs for the three green manure crops. In Western Canada, AC Green Fix chickling vetch sold for \$0.70 kg^{-1}, Trapper field pea sold for \$0.48 kg^{-1}, and Indianhead black lentil sold for \$0.66 kg^{-1} (Wagon Wheel Seeds of Churchbridge, SK; Gary Meier Core Farm of Ridgedale, SK; Johnson Seeds of Arborg, MB, personal communication, 2004). Seed weights were assumed to be 163 mg $seed^{-1}$ for field pea, 191 mg $seed^{-1}$ for chickling vetch, and 21 mg $seed^{-1}$ for black lentil.

The seed cost of each green manure species took into account their percent emergence. As percent emergence declined with increasing plant population density (Table 3.6), exponential regression using standardized percent emergence was used to estimate percent emergence for each green manure species and weed treatment from 24 to 400 plants m^{-2}. The following regression equations were used:

$$PE_{cvw} = 104.11\ e^{-0.0015TDgm} \quad [5.10]$$

$$PE_{cvwf} = 102.03\ e^{-0.0014TDgm} \quad [5.11]$$

$$PE_{fpw} = 92.73\ e^{-0.0011TDgm} \quad [5.12]$$

$$PE_{fpwf} = 101.7\ e^{-0.0015TDgm} \quad [5.13]$$

$$PE_{blw} = 97.4\ e^{-0.0050TDgm} \quad [5.14]$$

$$PE_{blwf} = 96.81\ e^{-0.0011TDgm} \quad [5.15]$$

where *PE* is percent emergence and TD_{gm} is green manure target density in plants m^{-2}. R^2 values for regression equations 5.10 to 5.15 were 0.96, 0.99, 0.74, 0.94, 0.72, and 0.85, respectively. To calculate seed cost ha^{-1}, target plant population density was then divided by *PE* and multiplied by seed weight in mg $seed^{-1}$, the cost of seed in \$ kg^{-1}, and a conversion factor of 1 000 000 mg kg^{-1}. Seeds cost m^{-2} was then converted to seed cost ha^{-1} using a conversion factor of 10 000 m^2 ha^{-1}.

5.2.6 Marginal revenue and marginal cost

The marginal cost of increasing green manure plant population density ha^{-1} and the marginal revenue of subsequent wheat yield increases ha^{-1} was then calculated for each green manure species. The plant population density at which the marginal revenue of wheat per unit of area equalled the marginal cost of green manure seed per unit of area determined the economically optimum plant population density for each green manure crop.

5.2.7 Net revenue

The net revenue of a subsequent wheat crop per unit of area, based on the nitrogen contribution of a green manure crop, was calculated using the following equation:

$$NR_w = R_w - P_{gm} \quad [5.16]$$

where NR_w is the net revenue of a subsequent wheat crop in \$ ha^{-1}, R_w is the total revenue of the wheat crop ha^{-1}, and P_{gm} is the seed cost of the previous green manure crop ha^{-1}. Net revenue was used to determine which of the three green manure species was most profitable to grow in terms of its nitrogen contribution to a subsequent wheat crop.

5.3 Results and Discussion

5.3.1 Model Recommendations

Marginal cost analysis determined the economically optimum plant population density for all three green manure crops based on their nitrogen contribution to a subsequent wheat crop. This analysis relied on two functions, marginal cost and marginal revenue (eg. Figure 5.1 or 5.2). The marginal cost of green manure seed increased with increasing green manure plant population density because of declining percent emergence (Table 3.6). Marginal revenue of predicted yield increases for a subsequent wheat crop declined with increasing plant population density. Two marginal revenue functions were included in the analysis. The high marginal revenue curve assumed 40% mineralization of green manure nitrogen in the first year and the low marginal revenue curve assumed 20%. The rate of decline in marginal revenue differed between the low and high marginal revenue functions.

The point at which the marginal revenue functions intersected the marginal cost function indicated the most profitable plant population density based on the assumed rate of green manure nitrogen mineralization. Under weed-free conditions, the recommended plant population density for black lentil was 223 plants m^{-2}

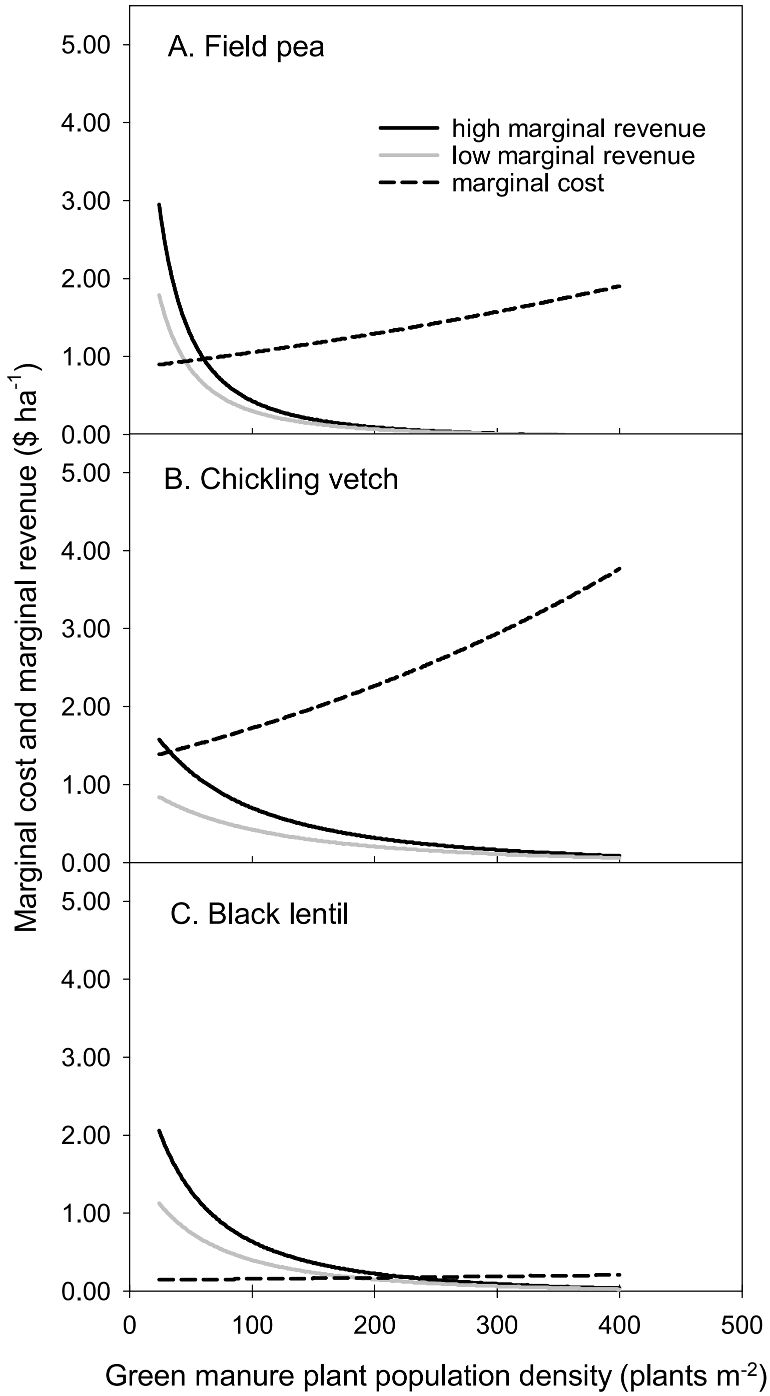

Figure 5.1: Marginal cost analysis of optimal plant population densities for (A) field pea, (B) chickling vetch, and (C) black lentil under weed-free conditions. High and low marginal revenue are based on the assumption of 40 and 20% nitrogen mineralization (respectively) of nitrogen found in incorporated green manure biomass.

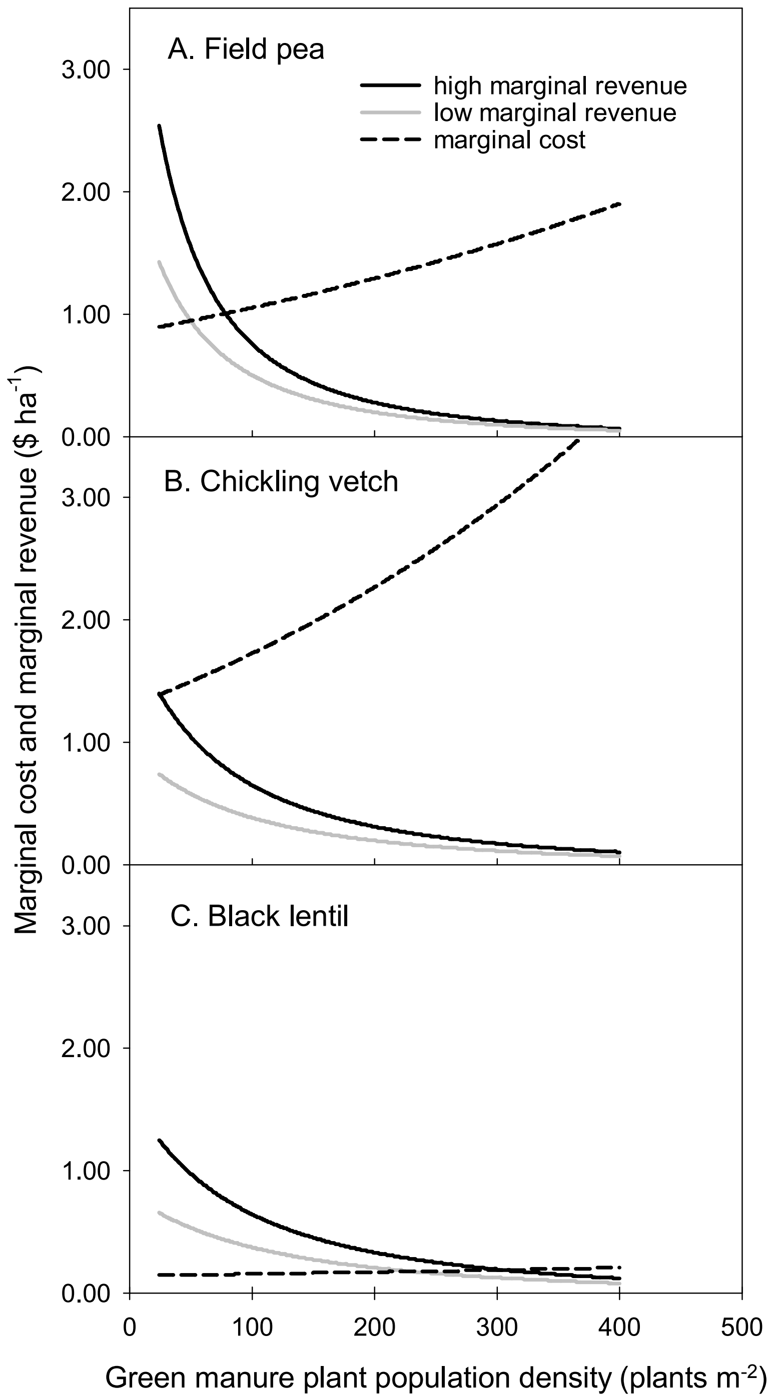

Figure 5.2: Marginal cost analysis of optimal plant population densities for (A) field pea, (B) chickling vetch, and (C) black lentil under weedy conditions. High and low marginal revenue are based on the assumption of 40 and 20% nitrogen mineralization (respectively) of nitrogen found in incorporated green manure biomass.

assuming higher nitrogen mineralization and 184 plants m^{-2} assuming lower mineralization (Figure 5.1 C). The optimal plant population densities for field pea was 60 plants m^{-2} assuming high nitrogen mineralization and 45 plants m^{-2} assuming low nitrogen mineralization (Figure 5.1 A). Under weed-free conditions, no profitable plant population density was found for chickling vetch at the lower nitrogen mineralization level because of its very high seed size and cost. However, when assuming the higher rate of nitrogen mineralization, the recommended plant population density was 32 plants m^{-2} (Figure 5.1-B).

Under weedy conditions, marginal cost analysis recommended higher plant population densities for black lentil and field pea than under weed-free conditions. For black lentil under weedy conditions, this intersection occurred at 300 plants m^{-2} when assuming the higher rate of nitrogen mineralization and at 223 plants m^{-2} for the lower rate (Figure 5.2 C). Black lentil has a very small seed size, making it possible to establish high plant population densities at a low cost. Under weedy conditions plant population densities for field pea were as high as 78 plants m^{-2} and as low as 49 plants m^{-2}. (Figure 5.2 A). Again, under weed-free conditions, no profitable plant population density was found for chickling vetch at the lower nitrogen mineralization level. When assuming the higher rate of nitrogen mineralization, the recommended plant population density was 24 plants m^{-2} (Figure 5.2 B).

Comparisons of the plant population density recommendations generated from marginal cost analysis reveal that plant population density recommendations for field pea are within the range or lower than the current plant population density recommendations for seed production of field pea at 60 to 90 plants m^{-2} (Park and Lopetinsky, Saskatchewan Pulse Growers, 2000; 1999; Wallace, 2001). However, plant population density recommendations for black lentil are higher than the current recommendations for seed production of black lentil at 80 to 130 plants m^{-2} (Park and Lopetinsky, Saskatchewan Pulse Growers, 2000; 1999; Wallace, 2001). Although no current plant population density recommendations exist for chickling vetch, the low plant population density for chickling vetch of 50 to 55 plants m^{-2}

used in some studies (Biederbeck et al., 1993; Bullied et al., 2002) seem appropriately low given the low profitability of chickling vetch.

5.3.2 Sensitivity Analysis

Sensitivity analysis was performed by increasing and decreasing the value of model assumptions. Reductions in the cost of green manure seed costs could be expected if producers grew their own seed for green manure crops. Decreasing the respective seed costs for field pea, chickling vetch, and black lentil green manure crops by 50% resulted in higher recommended plant population densities for all species (Table 5.3). The greatest percent change in recommended plant population densities as a result of lower seed costs occured for chickling vetch, followed by field pea.

Reductions in the value of organic wheat crops would be expected if they could not be sold with organic price premiums. Reducing the value of certified organic wheat by 50% decreased the recommended plant population densities for all species, but had the greatest effect on field pea (Table 5.3). Increasing the value of organic wheat crops is analogous to growing a higher value crop than wheat, assuming it had the same nitrogen response. Doubling the value of certified organic wheat increased the recommended plant population densities of all species (Table 5.3). The greatest percent change was seen for chickling vetch, followed by field pea (Table 5.3).

Decreasing soil nitrogen levels by 50% increased the recommended plant population densities of all species, while doubling soil nitrogen levels decreased them (Table 5.3). It is reasonable to assume lower soil nitrogen levels for organic fields in Saskatchewan than the provincial average of 19 kg ha^{-1} (Knight and Shirtliffe, 2003), as soil nitrogen levels were measured during wheat crop production. Wheat is presumably grown at a point the crop rotation when producers expect relatively high amounts of available soil nitrogen to achieve higher wheat yield and protein content (Wallace 2001). Green manure crops are grown at a point in the crop rotation where producers expect relatively low amounts of available soil nitrogen in order to improve nitrogen availability to subsequent crops.

Table 5.3: Sensitivity analysis of optimum plant population densities for three annual green manure crops when grown under weedy and weed-free conditions and when assuming a low and high nitrogen contribution to a subsequent wheat crop.

Type of change	Green manure species	Plant population density				Percent change plant population density			
		Weedy		Weed-free		Weedy		Weed-free	
		Low	High	Low	High	Low	High	Low	High
		plants m^{-2}				%			
Original model	Field pea	49	78	45	60	0	0	0	0
	Chickling vetch	0	24	0	32	0	0	0	0
	Black lentil	223	300	184	223	0	0	0	0
50% of seed costs for green manure crops	Field pea	97	126	73	90	98	62	62	50
	Chickling vetch	29	76	39	83	0	217	∞†	159
	Black lentil	342	400	255	400	53	33	39	79
50% of the price for certified organic wheat	Field pea	0	40	24	37	-100	-49	-47	-38
	Chickling vetch	0	0	0	0	0	0	0	-100
	Black lentil	120	192	118	155	-46	-36	-36	-30
200% of the price for certified organic wheat	Field pea	96	126	72	90	96	62	60	50
	Chickling vetch	29	76	39	83	0	217	∞†	159
	Black lentil	348	400	257	297	56	33	40	33
50% of the soil nitrogen level	Field pea	65	91	53	68	33	17	18	13
	Chickling vetch	0	42	0	49	0	75	0	53
	Black lentil	270	332	210	245	21	11	14	10
200% of the soil nitrogen level	Field pea	24	55	31	47	-51	-29	-31	-22
	Chickling vetch	0	0	0	0	0	0	0	-100
	Black lentil	152	236	145	188	-32	-21	-21	-16

† Percent increase in plant population density is infinitely larger.

Overall, changes to recommended plant population densities as a result of sensitivity analysis when based on lower estimates of nitrogen mineralization (20%) were greater than when based on higher estimates of nitrogen mineralization (40%). Although changes to model assumptions changed the plant population density recommendations for black lentil, changes in model assumptions resulted in greater changes in plant population densities for field pea and chickling vetch. It is likely that the optimum plant population densities for chickling vetch and field pea were more sensitive to changes in model assumptions because of their higher seed cost and seed size.

5.3.3 Net Revenue

Black lentil is more profitable than field pea or chickling vetch as a green manure crop under weedy and weed-free conditions, when considering the maximum net revenue of a subsequent wheat crop (Figure 5.3 and 5.4). Net revenue reflects the value of wheat yield increases based on the nitrogen contribution of a prior green manure crop and the green manure crop seed costs to achieve that wheat yield increase.

Under weed-free conditions, the highest net revenue occurred with black lentil, followed by field pea and chickling vetch. When assuming lower nitrogen mineralization, the maximum net revenue for black lentil was \$339 ha^{-1}, followed by field pea at \$326 ha^{-1}, and chickling vetch at \$254 ha^{-1}. When assuming higher nitrogen mineralization, the maximum net revenue for black lentil was \$418 ha^{-1}, followed by field pea at \$405 ha^{-1}, and chickling vetch at \$276 ha^{-1}.

Under weedy conditions, the highest net revenue still occurred with black lentil, followed by field pea and chickling vetch. When assuming lower nitrogen mineralization, the maximum net revenue for black lentil was \$316 ha^{-1}, followed by field pea at \$292 ha^{-1}, and chickling vetch at \$252 ha^{-1}. Net revenue increased when assuming higher nitrogen fixation. When assuming higher nitrogen mineralization, the maximum net revenue for black lentil was \$388 ha^{-1}, followed by field pea at \$359 ha^{-1}, and chickling vetch at \$271 ha^{-1}.

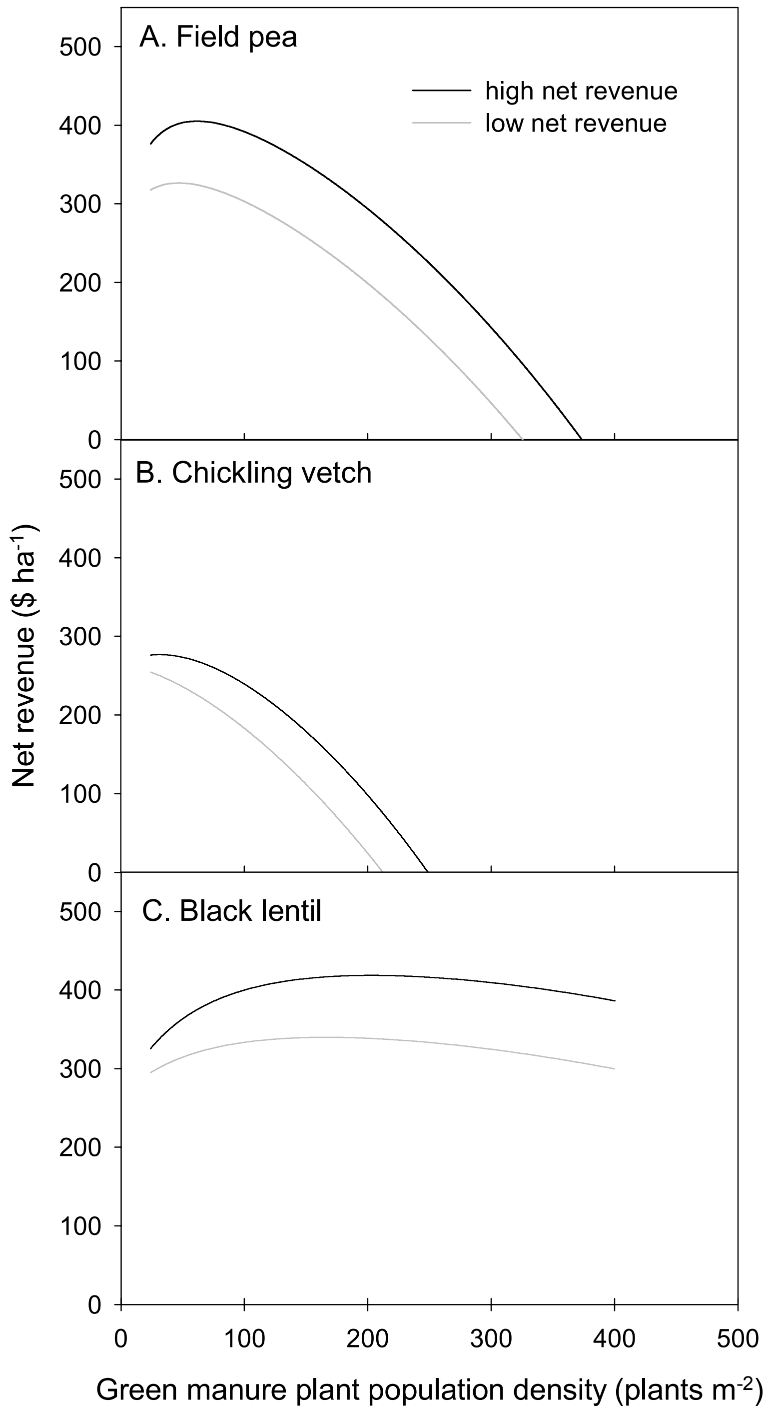

Figure 5.3: Net revenue of a wheat crop following (A) field pea, (B) chickling vetch, and (C) black lentil green manure crops grown under weed-free conditions. High and low net revenue based on the assumption of 40 and 20% nitrogen mineralization (respectively) of nitrogen found in incorporated green manure biomass.

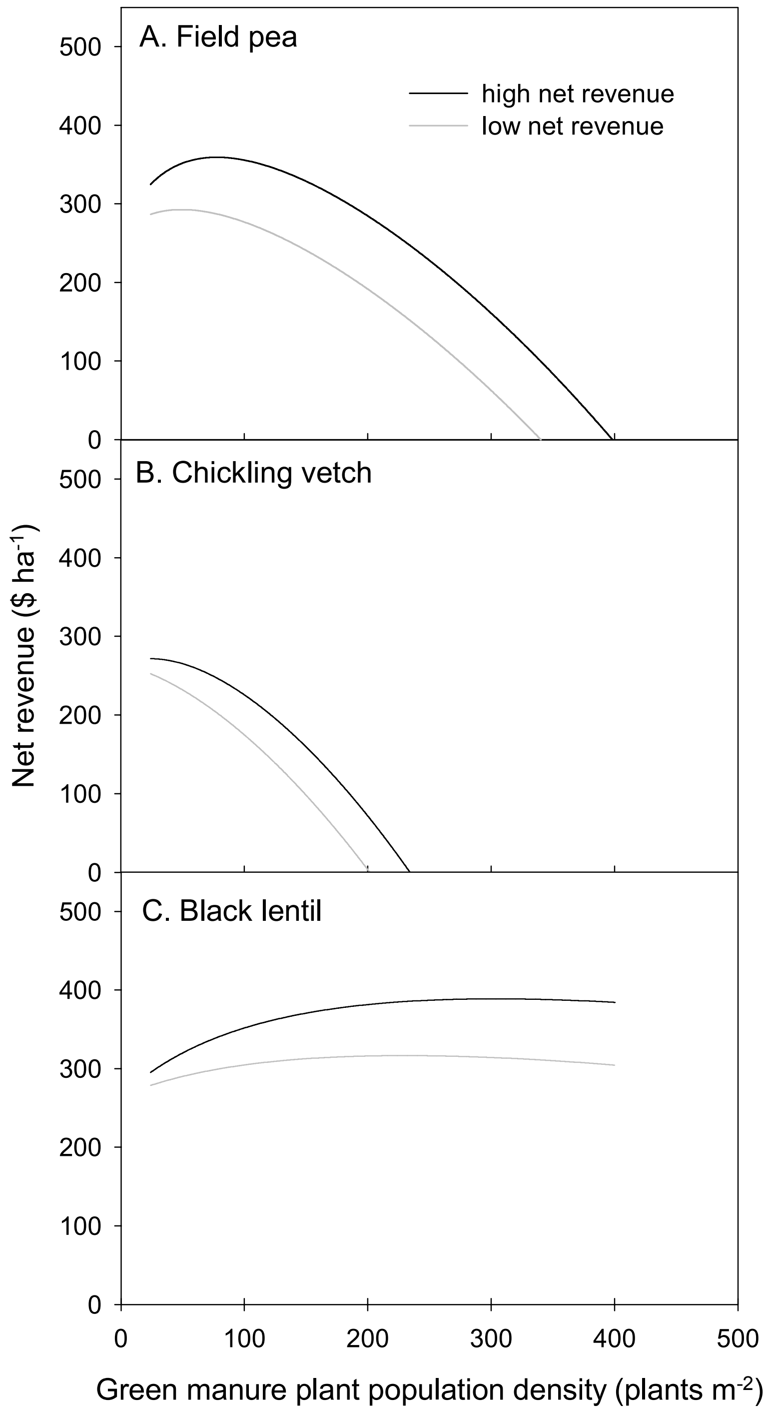

Figure 5.4: Net revenue of a wheat crop following (A) field pea, (B) chickling vetch, and (C) black lentil annual green manure crops grown under weedy conditions. High and low net revenue based on the assumption of 40 and 20% nitrogen mineralization (respectively) of nitrogen found in incorporated green manure biomass.

The finding that black lentil is a more profitable green manure crop than field pea or chickling vetch reinforces the importance of low seed costs for the profitability of green manure crops. The maximum profitability of black lentil under weedy conditions may be higher than was captured in this study as profitability increased continually across all plant population densities tested when assuming a higher rate of nitrogen mineralization. As well, the maximum profitability of chickling vetch may be higher at lower densities than were tested in this study when assuming a lower rate of nitrogen mineralization.

5.3.4 Comparisons to other models

The greatest difference between the models of French et al. (1994), Jettner et al. (1999), Seymour et al. (2002), and Shirtliffe et al. (2002) that determined optimum plant population densities for large seeded pulse crops and this model is their ability to use crop yield to determine crop revenue. Because there is no direct revenue from green manure crops, extra steps had to be taken in this model to estimate their value in terms of the yield of a subsequent crop. This process of estimation introduces greater error into the model, but is necessary to determine marginal revenue, as needed for marginal cost analysis.

Although the other models incorporated 10% opportunity costs into seed costs, it was not included in this model due to the recent trend of low interest rates. As well, using a 10% opportunity cost seemed arbitrary as Seymour at al. (2002) found large changes in opportunity cost, from 10 to 100%, did not significantly change plant population density recommendations.

5.3.5 Model limitations

Marginal cost analysis made it possible to determine optimum plant population densities for green manure crops, as it was able to account for the differing cost to produce equivalent amounts of biomass and accumulated nitrogen. However, it is difficult to construct a model that takes into account all of the benefits green manure crops in an organic cropping system because it is not yet possible to accurately estimate their value. This marginal cost analysis was based on the value of green manure crops in terms of their nitrogen contribution to the yield increase of one subsequent wheat crop. However, the model does not account for the role of nitrogen to increase grain protein levels. Higher grain protein increases the value of wheat and would increase the marginal revenue of a subsequent wheat crop, possibly resulting in higher optimum plant population density recommendations.

The model also does not take into account the value of increases in soil organic matter or nitrogen provided by green manure crops that is not mineralized within the first subsequent growing season. Bullied et al. (2002) observed yield benefits from green manure crops in both the first and second growing seasons following annual legume green manure crops. Janzen et al. (1990) found 37 to 72% of nitrogen in green manure residues remained in the soil profile after harvest of the first subsequent wheat crop. They argued that the primary advantage to green manure crops was their ability to replenish stable soil organic nitrogen reserves over the long-term, but it was not yet possible to assign a value to this long-term benefit.

Most importantly, this model does not account for the weed control benefits provided by green manure crops. As reported in Chapter 3, increasing green manure plant population density does result in significant reductions in weed biomass production. As well, some green manure crop species were better able to suppress weed growth. Thus, using green manure species with higher seed costs at higher plant population densities may become more economical if the value of their ability to suppress weeds could be quantified.

5.4 Summary

Because of its small seed size, black lentil is the most economical green manure crop. It had the highest net revenue, followed by field pea, and chickling vetch. Under weed-free conditions, marginal cost determined the range of optimum green manure plant population densities for black lentil to be 184 to 223 plants m^{-2} depending upon the amount of nitrogen mineralization from the green manure crop. Optimum plant population densities for field pea under weed-free conditions ranged from 45 to 60 plants m^{-2}. Under weed-free conditions an optimum plant population density for chickling vetch of 32 plants m^{-2} was determined when assuming higher nitrogen mineralization, but no optimal plant population density was found when assuming lower nitrogen mineralization.

Under weedy conditions, marginal cost determined the range of optimum green manure plant population densities for black lentil to be 223 to 300 plants m^{-2} depending upon the amount of nitrogen mineralization from the green manure crop. Optimum plant population densities for field pea under weedy conditions ranged from 49 to 78 plants m^{-2}. Under weed-free conditions an optimum plant population density for chickling vetch of 24 plants m^{-2} was determined when assuming higher nitrogen mineralization, but no optimal plant population density was found when assuming lower nitrogen mineralization. Sensitivity analysis revealed that decreasing green manure seed costs, increasing the price of wheat, and lower soil nitrogen levels resulted in higher optimum plant population density recommendations. Chickling vetch was more sensitive to changes in parameter assumptions than field pea or black lentil.

6.0 GENERAL DISCUSSION

6.1 Suitability of annual legume green manure species

Biederbeck and Looman (1985) and Brandt (1999) listed the desirable characteristics of annual legume green manure crops as: low seed cost, high nitrogen fixation, rapid growth rate, high water use efficiency, and good competitiveness with weeds. In light of the findings of this research it is possible to make stronger comparisons between field pea, chickling vetch, and black lentil in their suitability as annual legume green manure crops, especially in terms of their competitiveness with weeds and their relative seed costs.

Black lentil had the lowest seed cost and seed size of all three green manure species. This factor resulted in very high optimal plant population density recommendations for black lentil compared to the other two species and compared to recommended plant population densities for seed production of lentil. Although black lentil was shown to be the most economically favourable green manure crop, it did not rate well in terms of its competitiveness with weeds. It was shown to have the least ability to suppress weed biomass of all three species.

Field pea had the greatest ability to compete with weeds among all three crops. At very high densities, there was little difference in crop biomass production among weedy and weed-free conditions. High biomass production also resulted in field pea accumulating the highest levels of total nitrogen. Despite all these favourable characteristics, the optimum plant population density recommendations were lower than those recommended for seed production of field pea. This was most likely due to its relatively larger seed size and seed cost compared to black lentil. As well, the model determining optimum plant population densities did not take into account the value of weed control. Although it had higher seed costs than black lentil, field pea is the crop most suited to perform as a green manure crop under weedy conditions. Using higher rates than the optimum plant population density determined using this model may be profitable when the value of weed control is considered.

Chickling vetch had comparable weed suppression to field pea despite having similar levels of biomass production to black lentil. The lower biomass accumulation of chickling vetch limited its nitrogen contribution to subsequent crops. It was expected that chickling vetch would be shown to have high water use efficiency (Biederbeck and Bouman, 1994), but this was not evident in the results. The limited nitrogen contribution of chickling vetch, combined with its very large seed size and seed cost, made chickling vetch the least economically feasible crop of the three compared. The seed costs for chickling vetch is the most limiting factor to its success as an annual legume green manure crop and producers should consider growing their own seed.

The findings of this research suggest that among the criteria for successful annual legume green manure crops, low seed cost is one of the most important factors. This is evident by the high optimum plant population density recommendations for black lentil, the least competitive green manure species, and the lack of optimum plant population densities for chickling vetch. As well, this study found that maximizing the nitrogen contribution of green manure crops was primarily dependent on their ability to produce biomass. This indicates that a species potential biomass production should also be considered as a criterion for the ideal green manure crop.

6.2 Considerations for green manure crop management under weedy conditions

The results of this study indicate that green manure crops should be managed differently under weedy conditions. Optimum plant population density recommendations generated from marginal cost analysis were usually higher under weedy conditions for field pea and black lentil. This trend was not seen for chickling vetch, as sufficiently low plant population densities were not included in this study to allow the model to adequately predict optimal plant population densities. It is interesting to note that the amount of weed biomass was similar for both field pea and black lentil production (approximately 1000 kg ha^{-1}) at their optimal plant populations (Figure 3.5).

Differences between weedy and weed-free treatments, in terms of soil water use and total nitrogen accumulation, diminished as green manure plant population density increased. This suggests that the presence of weeds in a green manure crop can be beneficial in term of increasing biomass and total nitrogen accumulation, provided the stand can be terminated before the weeds produce seed. However, there is always the risk of weather interfering with the ideal timing of green manure termination. In wet years, green manure stand termination may be delayed due to poor field conditions. This could be a greater problem when growing black lentil. As seen in Figures 3.5 and 3.6, the increase in weed biomass was much greater between early bud and full bloom for black lentil than for field pea. Thus, where there is risk of crop management delays, it may be beneficial to plant a more competitive green manure crop, such as field pea.

6.3 Plant population density recommendations

Marginal cost analysis made it possible to determine economically optimum plant population densities for field pea, chickling vetch, and black lentil annual green manure crops. This unique approach considered the value of nitrogen from green manure crops to subsequent wheat crops and generated a range of optimal plant population densities based on an assumed amount of nitrogen mineralization. However, this model was unable to account for the full value of green manure crops, in term of their contribution to weed control or soil organic matter, and stopped short of making one conclusive plant population density recommendation for producers.

Sensitivity analysis of the marginal cost model (Chapter 4) gives some guidance for making an overall recommendation for green manure plant population densities. Shirtliffe and Knight (2003) found average soil nitrogen levels in organically managed fields to be 19 kg ha^{-1}. It is not unreasonable to assume that average soil nitrogen levels could be even lower at a point in the crop rotation where green manure crops are included. At these low soil nitrogen levels, subsequent crop yield could be very responsive to any nitrogen made available following green manure crop incorporation. This situation closely fits the conditions described in the sensitivity analysis that assumes a 50% reduction in soil nitrogen levels and a 40% rate of nitrogen mineralization. Thus, under organic management conditions, the most suitable plant population densities for field pea, chickling vetch, and black lentil under weedy conditions are 90, 40, 330 plants m^{-2}, respectively and under weed-free conditions are 70, 50, and 245 plants m^{-2}, respectively.

6.4 Need for future research

There is a great need for organic cropping systems research in Saskatchewan. As of 2002, Saskatchewan had both the largest number of certified organic producers (1150 producers) and the largest number of acres in organic production (760 000 acres) in all of Canada (Macey, 2004). The number of organic producers grew by 475% between 1992 and 2002 (Macey, 2004). If the trend for increasing organic production in Saskatchewan and throughout Canada continues, a detailed understanding of the role and function of green manure crops in organic crop production systems is critical. Two of the most limiting factors to organic production are soil nutrient levels and weed control (Wallace, 2001; Knight and Shirtliffe, 2003) Green manure crops have a role to play in addressing both of these problems.

Knight and Shirtliffe (2003) highlight the severe nutrient deficiencies experienced in organic fields across Saskatchewan. More research is needed to understand the extent of crop response to nutrients provide by green manure crops under severely nutrient deficient soil and across a range of nutrient level inputs. As well, phosphorous deficiencies are of particular interest under organic conditions. More research is needed to determine the extent of phosphorous cycling using green manure crops.

This has been the first major study examining the role of annual green manure legumes in providing weed control. Further research is needed to determine the value of weed control and soil organic matter to improve the model used to determine optimal plant population density recommendations used in this study. Research is also needed to determine the optimal timing of green manure stand termination and crop seeding for weed control. The results of this study indicate that plant population density recommendations for seed production of similar varieties are not appropriate for green manure crops. Optimal plant population density recommendations should also be developed for the many other annual, biennial, and perennial legume green manure crops. Of particular interest would be crops such as yellow sweet clover and alfalfa. As well, plant population density studies would help determine the feasibility of new green manure crops.

Although the model used in this thesis to determine optimum plant population densities for the three annual green manure legumes is unique in that it takes into account the value of green manure crops to a subsequent wheat crop, it only focuses on short-term benefits. However, green manure crops are primarily used to overcome long-term problems. Thus, studies comparing the management practices of green manure crops and the effect of different green manure species must be examined within the context of long-term crop rotation studies. This approach is needed to determine if green manure crops can be valued as a practice that contributes to the long-term sustainability of organic cropping systems.

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