OPTIMAL SEEDING RATES

FOR ORGANIC PRODUCTION OF FIELD PEA AND LENTIL

A Thesis

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Julia M. Baird

PERMISSION TO USE

ABSTRACT

There are no seeding rates established for organic production of field pea and lentil in Saskatchewan and organic producers must rely upon rates recommended for conventional production of these crops. These seeding rates may not be suitable for organic production as the two systems differ in the use of inputs and in pest management. The objectives of this study were to determine an optimal seeding rate for organic production of field pea and lentil in Saskatchewan considering a number of factors, including yield, weed suppression, soil nitrogen (N) and phosphorus (P) concentrations, soil water storage, colonization of crop roots by arbuscular mycorrhizal fungi (AMF), plant P uptake, and profitability. A field experiment was conducted to determine the optimal seeding rates of field pea and lentil. Field pea seeding rates were 10, 25, 62, 156 and 250 plants m^{-2} and lentil seeding rates were 15, 38, 94, 235 and 375 plants m^{-2}. Seeding rates were determined using a multiplier of 2.5. Sites were established at Vonda, Vanscoy and Delisle, SK using a randomized complete block designs with summerfallow and green manure treatments included for each crop. Soil and plant samples were taken throughout the growing season and analyzed for physical and chemical properties.

Seed yield increased with increasing seeding rate for both crops, up to 1725 kg ha^{-1} for field pea and 1290 kg ha^{-1} for lentil. Weed biomass at physiological maturity decreased with increasing seeding rate for both crops. In field pea, weeds were reduced in weight by 68%, while lentil reduced weed biomass by 59% between the lowest and highest seeding rates.

Post-harvest soil phosphate-P levels did not change consistently between treatments, indicating that there was no trend in soil P concentration with seeding rate. Post-harvest soil inorganic N, however, was higher for the summerfallow and green manure treatments than for the seeding rate treatments in both crops. Inorganic N was higher at some sites for the highest two seeding rates in field pea. Soil water storage following harvest was not affected by treatment.

Colonization of crop roots by AMF increased for lentil with increasing seeding rate, but the same trend was not observed in field pea. A growth chamber experiment to study the rate of colonization of field pea between 10 and 50 d after emergence did not show any differences in AMF colonization between seeding rates. Colonization levels were high (70 to 85%) for both crops in both the field and growth chamber. Arbuscular mycorrhizal fungi colonization and seeding rate had no effect on plant P concentration for either field pea or lentil.

Both crops became increasingly profitable as seeding rate increased. Field pea reached a maximum return at 200 plants m^{-2} and lentil return increased to the highest seeding rate of 375 plants m^{-2}. Organic farmers should increase seeding rates of these crops to increase returns and provide better weed suppression.

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DEDICATION

This thesis is dedicated to my dad, Ken Dalke, who has been a source of inspiration in his work ethic, his belief in the importance of agriculture and his commitment to his family.

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LIST OF ABBREVIATIONS

a	Upper asymptote in four-parameter logistic equation
ac	Acre
AMF	Arbuscular mycorrhizal fungi
Ap	Cultivated A horizon
b	Slope factor in four-parameter logistic equation
c	Constant in three-parameter modified Michaelis-Menten equation
C	Carbon
CEC	Cation exchange capacity
cfu	Colony-forming units
CGC	Canadian Grain Commission
CGSB	Canadian General Standards Board
CI	Competitive indices
cm	Centimeter
d	Day
D	Plant density
DAE	Days after emergence
DAP	Days after planting
df	Degrees of freedom
EC	Electrical conductivity
g	Gram
GDD	Growing degree days
h	Hour
ha	Hectare
HI	Harvest index
K	Potassium
kg	Kilogram
Ln	Natural log
m	Metre
mg	Milligram
min	Minute
mL	Millilitre
mm	Millimetre
mS	Millisiemen
N	Nitrogen
NS	Not significant
OCIA	Organic Crop Improvement Association
OCPP	Organic Crop Producers and Processors
P	Phosphorus
P	Probability
PT	Growing season precipitation
R	Return
R^2	Coefficient of regression
Rep	Replicate
s	Second

SE	Standard error
SK	Saskatchewan
SOM	Soil organic matter
SR	Seeding rate
SY	Site-year
T	Temperature
WUE	Water use efficiency
x_0	Days after emergence where half of P uptake occurs
y	Year
Y	Yield
y_0	Lower asymptote of four-parameter logistic equation
μg	Microgram
μmoles	Micromoles
θ	Soil water

1. INTRODUCTION

The province of Saskatchewan supports the largest number of certified organic farms in Canada, and produces the majority of organic field pea and lentil in the country (Macey, 2006). More than 300,000 ha are devoted to organic production in Saskatchewan with 21% of that land area used to produce field pea or lentil in 2005 (Macey, 2006).

Organic production systems typically are regarded as holistic in nature and can be distinguished from conventional systems in a number of ways: land used for organic agriculture is free of synthetic fertilizers, producers are prohibited from using synthetic pesticides and genetically modified organisms, and there is a focus on long-term environmental sustainability (CGSB, 2006).

Producers must abide by standards to have their products certified as organic and be able to obtain premiums are paid for organically-produced commodities (Stockdale et al., 2001). National standards in Canada have recently been established by the Canadian General Standards Board (CGSB) which is a federal agency. These standards are not ‘law’, but rather voluntary guidelines to follow for the production of certified organic products (CGSB, 2006). Producers may choose the certification body they wish to be associated with and the standards complied with depend on the certification body chosen (eg. OCPP/Pro-Cert, OCIA and EcoCert all certify organic producers in Saskatchewan). Depending on the certification body chosen, the standards producers must comply with may vary slightly, but follow the same principles. The CGSB standards provided for Canadian organic producers include a list of prohibited substances, especially fertilizers and pesticides (CGSB, 2006). Organic producers must find alternative ways to maintain soil fertility and manage weeds since pesticides and synthetic fertilizers can not be employed. One way farmers maintain soil fertility is through the incorporation of pulse crops into their rotation (CGSB, 2006; SOD, 2000).

Pulse crops are an important part of an organic crop rotation. Organic pulse seed garners high premiums and can be a good source of income for farmers (University of Saskatchewan, 2006). These crops also fix up to 80% of their nitrogen (N) requirement from atmospheric N via N_2 fixation and can provide a positive N balance for the following crop (Corre-Hellou and Crozat, 2005). Nutrient availability in organically managed soils can be low and growing pulse crops are an important way to maintain soil nutrient levels. Incorporation of a legume cash crop into the crop rotation can help maintain soil N and increase the number of years between a fertility-building green manure or perennial crops (Stockdale et al., 2001).

In Saskatchewan, field pea and lentil are grown as cash crops by both organic and conventional farmers, but there is no recommended seeding rate for production of these legumes for organic systems (Statistics Canada, 2007; CGSB, 2006). Managing weeds in organically grown pea and lentil is important to maximize growth and N_2 fixation. Increased seeding rates may provide a competitive advantage to the crop, thereby promoting greater yields and profitability.

The objective of this study was to determine how seeding rate of organic field pea and lentil affects the production system as a whole. Several components within the production system were examined, namely i) weed density; ii) soil N and P concentrations; iii) arbuscular mycorrhizal fungi (AMF) colonization of crop roots and plant uptake of P; iv) soil water storage; v) crop yield; and vi) profitability.

The ultimate goal of this organic production system study was to determine an economic optimal seeding rate for both field and lentil for organic production in the Northern Great Plains.

2. LITERATURE REVIEW

2.1 Organic Production Principles

The goal of organic production systems is to operate in a manner that is sustainable and in harmony with the environment (CGSB, 2006). There are a number of principles associated with this goal that revolve around a holistic focus, diversity and sustainability.

2.1.1 Holistic focus

The focus in organic agriculture is on the long-term health of the system (Stockdale et al., 2001). Extended crop rotations are encouraged and often include a number of different 'phases' (i.e., fertility-building crops, nutrient-depleting crops) (Stockdale et al., 2001; Bàrberi, 2002). The concept that all aspects of agricultural production are not independent of one another is central to the organic production philosophy (Köpke, 1995). Planning a production system that maintains or increases water, organisms, air and the quality of the soil is encouraged. Studies have found that soils amended with organic nutrient inputs, as opposed to synthetic fertilizer inputs, had increased soil organic matter, carbon, cation exchange capacity (CEC), soil microorganisms and decreased soil pathogens and bulk density, resulting in increased soil quality (Drinkwater et al., 1995; Bulluck et al., 2002).

2.1.2 Biodiversity

A major focus of organic agriculture is maintaining biodiversity (Tamm, 2001). Organic farmers surveyed in Saskatchewan indicated that they used crop rotations with a cycle length of five to 10 years (Molder et al., 1991). Increased diversity in crop rotation allows for a number of life strategies to be used (Stockdale et al., 2001). This in turn may manage a variety of weed species, as they will not be able to adapt to a particular management schedule (Stockdale et al., 2001). Diversity in crop life strategies encourages the use of perennials and biennials as well as annual crops in the rotation.

Crops such as alfalfa can be grown for more than one year, offering soil erosion protection and increased soil N through atmospheric N_2 fixation (Watson et al., 2002a). Increased crop diversity also allows for utilization of crops with different rooting patterns to access moisture and nutrients from various depths in the soil profile (Watson et al., 2002a). A shallow-rooted crop may be followed by a deep-rooted crop to increase plant-available nutrients and water for both crops.

Organic farmers view weeds as a source of biodiversity and habitat for beneficial insects (Turner et al., 2007) and this has been shown to be the case in several studies. Manhoudt et al. (2007) found an increase of 38% to 47% in plant species richness in ditch banks around organic fields as opposed to conventional fields. A study performed by Mäder et al. (2002) found greater diversity of weed species in organic systems (nine to 11 species) than in conventional systems (one specie). In addition, more carabid species (beneficial beetles that prey on insect pests and weed seeds) and greater microbial diversity were found in organic and bio-dynamic systems than in conventional systems. A study performed in Michigan found that total carabid numbers were similar between conventional, no-till and organic systems, but no-till and organic systems showed the greatest species diversity and evenness (Menalled et al., 2007).

Microorganism abundance also may be affected by the variety of plant species growing in a given location. Chen et al. (2005) found that arbuscular mycorrhizal fungi (AMF) spore numbers were higher in sites with plant mixtures than in monocultures.

2.1.3 Sustainability

Organic farming systems may be more sustainable than conventional systems (Pacini et al., 2003). Sustainability can be measured in a number of ways. Soil nutrient sustainability is important; Saskatchewan organic farmers surveyed ranked "Maintaining and/or improving soil quality" as their most important goal in converting from conventional farming to organic, above increasing profits (Molder et al., 1991).

Sustainability of the system must also be considered in terms of profitability. Organic farms can be more profitable than their conventional counterparts if premiums exceed the cost of reduced yields (Stockdale et al., 2001). Pacini et al. (2003) agreed that organic farms were more profitable than conventional farms due to premiums paid for organic commodities and lower costs associated with pest management.

2.2 Important Aspects of Organic Production Systems

There are particular aspects of production in organic systems that require careful consideration when incorporating a crop into a rotation, namely weed abundance and soil fertility. These factors are important because they are the main constraints to production in agricultural systems, but particularly in organic production due to the restrictions on inputs imposed on the system (Mason and Spaner, 2006).

2.2.1 Weed abundance

Field pea and lentil in particular are known to be poorly competitive with weeds (Wall et al., 1991; Wall and Townley-Smith, 1996; Ball et al., 1997; Harker, 2001). Yield losses due to weed interference can be devastating (Makowski, 1995; Harker, 2001; Tepe et al., 2005). Weed abundance has been cited as a major problem in organic production systems (Sahs and Lesoing, 1985). Although weed biodiversity is widely reported to be higher in organic systems than conventional, there is some debate about whether or not weed densities are greater. Ngouajio and McGiffen (2002) argue that weed populations are not necessarily higher in organic production systems than conventional ones due to the use of green manure crops and cover crops which reduce weed severity. Leeson et al. (2000), however, found that organic farms had a higher number of weeds after post-emergent weed control than conventional farms.

Many studies suggest that the severity of weed interference is largely due to environmental factors, particularly precipitation (Lutman et al., 1994; Harker, 2001). When moisture is readily available, weed numbers and biomass increase, as do crop yield losses due to weed interference (Lutman et al., 1994; Harker, 2001). This makes weed management in organic systems more difficult, as precipitation may vary markedly between growing seasons. Organic farmers, therefore, must maximize the competitive ability of the crop to reduce yield losses despite potentially high weed densities.

Methods to manage weeds in organic field crop production include the use of mechanical, cultural and, in some cases, chemical, thermal and/or biological means

(Stockdale et al., 2001). The mechanical method used extensively in organic farming systems is tillage (Mohler, 2001). Farmers may till a few days prior to seeding the crop, then again directly before seeding (stale seedbed technique), and may make an additional shallow tillage pass when the crop and weeds are young to cover or uproot weed seedlings (Mohler, 2001).

Cultural weed management methods include the use of competitive cultivars, narrow row spacing and varying seeding rate to increase the competitive ability of the crop (SOD, 2000). Organic farmers often use legume green manure crops to both increase soil fertility and manage weed species (SOD, 2000). Green manure legumes are effective as a management tool for annual weeds because weeds are incorporated into the soil before seeds are set, reducing weed seed bank numbers (SOD, 2000). Increasing the crop density has been shown to reduce weed densities (Townley-Smith and Wright, 1994), and is commonly used in organic agricultural systems as a cultural weed management strategy together with other practices (SOD, 2000; Stockdale et al., 2001; Nazarko et al., 2003).

Some producers also may use thermal or non-restricted chemical means to reduce weed numbers, although these methods are less widely adopted (Stockdale et al., 2001). Thermal weed control involves the use of fire or steam to physically damage weeds, although the benefits may be precluded by the cost of fuel for these methods (Mohler, 2001). Some chemical preparations are allowed for use in organic farming, an example is the use of vinegar (acetic acid) to spot-spray weeds (CGSB, 2006). Biological weed management uses living organisms, such as herbivores and pathogens, to reduce weed growth (Liebman, 2001). This method of weed management may become more important in the future, as products become readily available to farmers (Liebman, 2001).

2.2.2 Soil fertility

Fertility in organic systems is largely dependent upon soil processes (Stockdale et al., 2001; Stockdale et al., 2002). Soil nutrient levels in organic production systems are also highly dependent on individual management and time under organic production, but are generally considered to be lower than in conventionally-managed soils (Watson et al., 2002b; Gosling and Shepherd, 2005). Soil fertility in organic systems is largely dependent upon the nature of additions to the soil (i.e., crop residues only vs. manure). Mäder et al. (2002) found that nutrient inputs into organic systems were 34 to 51% lower than in conventional systems. Tamm (2001) argues that soils under long-term organic management show no decrease in fertility, and Sahs and Lesoing (1985) found that soils managed organically had higher levels of soil organic matter, N, potassium (K) and P when amended with manure than conventionally-managed soils.

Two macronutrients that are commonly discussed in organic research are N and P (Drinkwater et al., 1998; Clark et al., 1999; Entz et al., 2001; Berry et al., 2002; Malhi et al., 2002; Oehl et al., 2002; Watson et al., 2002b; Gosling and Shepherd, 2005).

2.2.2.1 Nitrogen

Inorganic N is often found in similar concentrations in both organically- and conventionally-managed soils (Clark et al., 1999; Entz et al., 2001; Gosling and Shepherd, 2005), and many mixed organic farms have demonstrated positive N balances, meaning more N is added to the system through manure and/or N_2 fixation than is lost through grain sold (Sahs and Lesoing, 1985; Watson et al., 2002b). These positive N balances result from the addition of cattle manure and the inclusion of legumes in the crop rotation, which provided additional N through N_2 fixation (Sahs and Lesoing, 1985; Watson et al., 2002b). Haynes et al. (1993), however, found a negative N balance after growing legumes. This study did not include the application of animal manure as a nutrient input, but rather relied solely on the N_2 fixing power of the legume grown as a grain crop.

The incorporation of legumes into an organic crop rotation may not provide enough N input through N_2 fixation to maintain soil N levels. The narrow carbon (C):N ratio of legumes means that residues quickly decompose (Drinkwater et al., 1998; Gosling and Shepherd, 2005). Nitrogen (N) availability during the period of crop growth may be limited (especially when legumes are incorporated mid-way through the growing season) and may not supply N when needed to the following crop due to rapid decay of residues, although the rate of decay is dependent upon climatic conditions.

Bremer and van Kessel (1992) found that grain legume straw decomposed more slowly than legumes used as a green manure, which may provide a more appropriately-timed source of plant-available N during the growing season.

2.2.2.2 Phosphorus

Low soil P levels are thought to reduce N_2 fixation by legume crops (Oberson et al., 2007). In a study by Malhi et al. (2002) higher soil N levels in an organic production system than a reduced-input production system were suggested to occur due to the very low levels of P, limiting crop growth and uptake. There are a range of mechanisms plants can use to increase P acquisition, including specialized root structures, increased root growth and associations with soil microorganisms, specifically AMF (Richardson, 2001; Gahoonia et al., 2005).

The interaction between biological and chemical soil processes is important in organic production systems for regulating plant-available P (Stockdale et al., 2002). An important factor in determining supplying power of the soil for plant-available P is soil organic matter (SOM) (Havlin et al., 1999; Grant et al., 2002). Increased residues will increase the rate of biological processes, as organic matter provides energy to fuel microbiological activity (Stockdale et al., 2001; Stockdale et al., 2002). Labile, or plant-available P, is found in the soil as microbial, adsorbed or solution P, and is readily accessible by plants. Depletion of the labile pool of P causes some non-labile P such as primary and secondary minerals to become labile, but at a slow rate (Havlin et al., 1999). The importance of returning residue to the soil becomes greater over time as P decreases in the soil profile (Oehl et al., 2002). There is a general consensus that P concentrations in organically-managed soils are depleted over time, especially where legume green manure crops are not incorporated into a rotation (Entz et al., 2001; Mahli et al 2002; Oehl et al., 2002; Gosling and Shepherd, 2005).

2.3 Benefits of Grain Legumes in an Organic Crop Rotation

2.3.1 Disease break

Many field crop diseases are host-specific and a break between cereal crops can reduce disease incidence (Stockdale et al., 2001). Diversified crop rotations may improve disease management, as many diseases require a specific species to proliferate (Stockdale et al., 2001). Reducing disease occurrence in organic systems is important as commercial fungicides are prohibited (CGSB, 2006). Pulses can provide an important break between cereal crops to reduce incidence of disease in the crop rotation (Bailey, 1996). In a Saskatchewan study, a wheat monoculture showed higher disease incidence than wheat in a four-year rotation with oilseeds and legumes. Stevenson and van Kessel (1996) found a lower incidence in root rot severity when wheat followed pea, as compared with wheat following wheat at one site, but no difference at another. Gan et al. (2006) suggest that the number of crops in rotation to reduce disease severity depends on the climate of the area – warm and moist environments require less time for residue decomposition and can support shorter rotations. However, Bailey et al. (2000) found that crop rotation had no effect on disease, and that environmental factors were most important when determining severity of disease. These diverse findings indicate the challenges involved in determining optimal cropping systems in various Agro-Ecological zones.

2.3.2 Nutrient availability

Legume crops can increase nutrient availability to following crops due to the easily-decomposing residue and narrow C:N ratio (Gosling and Shepherd, 2005). Legumes also reduce the amount of soil N used in a growing season, as they form associations with *Rhizobium* species and acquire much of their N requirement from atmospheric N_2 (Köpke, 1995; Matus et al., 1997).

Nitrogen fixation by legumes is strongly influenced by soil water content. The proportion of N supplied by field pea or lentil to the following crop, therefore, may vary considerably based on climatic conditions (Carranca et al., 1999; Schmidtke et al., 2004). In a European study, field pea supplied 100 kg N ha^{-1} with adequate soil moisture and only 37 kg N ha^{-1} when drought conditions persisted (Carranca et al., 1999). Similarly, Schmidtke et al. (2004) found that lentil grown for grain in central Europe returned over 55 kg N ha^{-1} under moist conditions with low inorganic N, but less (1 kg N ha^{-1}) under drier conditions where inorganic N was higher.

Nitrogen fixation by legumes may also be sensitive to seeding date. In an Australian study, field pea fixed substantially more N when sown in early May than in early June (59 kg N ha^{-1} and 7.5 kg N ha^{-1}, respectively) (O'Connor et al., 1993).

Under conventional tillage, the amount of N derived from the atmosphere in grain was 48.4% for field pea and 61.6% for lentil (Matus et al., 1997). A Saskatchewan study determined that there was an N benefit from pea to the succeeding crop of 6 to 14 kg N ha^{-1} (Stevenson and van Kessel, 1996). In a German study, lentil provided a slightly negative N balance (-0.8 to -4.3 kg N ha^{-1}) (Schmidtke et al., 2004). Another German study presented a very different outcome; field pea provided between 77 and 109 kg N ha^{-1} when only the grain was removed (Maidl et al., 1996). In the study by Maidl et al. (1996), all nutrients were supplied at optimal levels and rainfall was adequate.

Janzen and Kucey (1988) suggest that N decomposition rate is directly related to N concentration in the residue. There is some debate as to how beneficial the N from green manure legumes is; the rapidly decomposing residue may lead to increased N leaching rather than N accumulation for plant growth when environmental conditions are conducive to leaching (Köpke, 1995; Watson et al., 2002a). However, grain legume residue decomposes at a slower rate than green manure legume residue, and may reduce N losses from leaching which can reach 78 kg NO_3-N ha^{-1} (Köpke 1995; Maidl et al., 1996). These findings are supported by Campbell et al. (1992) who found that there was a "good synchrony" between N release through decomposition and N uptake by the following crop from legume straw. These findings also highlight the impact of soil moisture and temperature impacts on decomposition and nutrient release from crop residues.

Including field pea in a crop rotation can provide advantages to the following crop other than increased N availability. Stevenson and van Kessel (1996) found that wheat following pea benefited from increased availability of P, K and S. It is possible that enhanced nutrient uptake was due to beneficial microbial associations such as AMF.

2.3.3 Root colonization by AMF

Arbuscular mycorrhizal fungi are ubiquitous in soil (Mosse et al., 1981) and colonize approximately 80% of all plant species, including field pea and lentil (Smith and Read, 1997). These endomycorrhizae colonize plant roots and form potentially symbiotic associations that provide the plant with a number of potential benefits, including disease suppression (Rosendahl, 1985; Harrier and Watson, 2004), increased drought tolerance, soil stability, increased N fixation by *Rhizobium* bacteria and increased nutrient uptake (Dodd, 2000). Arbuscular mycorrhizal fungi effectively extend the root systems of plants allowing for greater nutrient uptake while plants supply the fungi with C as an energy source (Gupta et al., 2000). Plants with different root systems have varying dependency on AMF for nutrient uptake – cereal crops with fast-growing fibrous roots generally show a lower rate of colonization than crops with slower root growth such as field pea and lentil (Smith and Read, 1997). In organic production systems where P is generally limiting, this symbiosis between crops and AMF is especially important, as AMF contribute to soil-immobile nutrient uptake (Harley and Smith, 1983). Phosphorus availability has been identified as a limiting factor in N-fixation by legumes (Ozanne, 1980). With a high rate of AMF colonization in soil where P availability is low, more P can be accessed from the soil for plants through absorption from an extensive hyphal network (Harley and Smith, 1983), thereby increasing potential uptake of other nutrients. Soils used in organic production systems have often shown greater colonization of roots by AMF as well as greater species diversity than soils under conventional management (Mäder et al., 2000; Oehl et al., 2004). In a long-term production system comparison study, Oehl et al. (2004) found 19 species of AMF spores in the organically-managed plots and 15 species in the conventionally-managed plots. More AMF spores per gram of soil were also found in the organic plots as compared to the conventional plots (12.5 spores g soil^{-1} and 10.0 spores g soil^{-1}, respectively). In the same experiment, Mäder et al. (2000) found an increase in AMF colonization of plant roots in the organic plots over the conventional plots. The reason for higher species diversity, number, and colonization is likely that the addition of P fertilizer to soil decreases AMF activity, thereby decreasing numbers and ultimately diversity (Mäder et al., 2000; Oehl et al., 2004). An increase in AMF colonization of crop plants in organic production systems, however, may not equate to an increase in yield. Galvez et al. (2001) found that increased AMF colonization in maize in a low-input system due to reduced tillage did not provide enough of a benefit to the crop to offset losses caused by high weed biomass.

Many studies have found that seeding rate has an effect on AMF colonization levels. A number of these studies reported decreased AMF colonization with increasing plant density (Jakobsen and Nielsen, 1983; Abbott and Robson, 1984; Koide and Dickie, 2002; Schroeder and Janos, 2005). Warner and Mosse (1982), however, found that increasing the density of clover increased colonization when AMF inoculum originated from a single location.

While much research has been devoted to the study of plant density and AMF colonization rates or AMF colonization levels between conventional and organic systems, no research has been conducted examining whether colonization levels change with seeding rates within organic production systems.

2.3.3.1 Role of host and non-host weeds

Weeds that are mycotrophic (hosts) and non-mycotrophic (non-hosts) can have varied effects on AMF colonization and the associated benefits to host crops. In a study by Feldmann and Boyle (1999), maize yield increased when weeds that were non-hosts of AMF were removed from the crop. Maize yields decreased when weeds that hosted AMF were removed from the crop. In another study, non-host weeds were found to either have no effect or a negative effect on highly mycorrhizal plant species (Chen et al., 2005). These findings are further supported by Fontenla et al. (1999) who found that colonization of pea was neutral or reduced in the presence of non-host weeds than when grown without. The reduction in colonization by AMF occurred when non-host weeds emerged and established before the crop.

Koide and Dickie (2002) found that seeds from mycorrhizal *Abutilon theophrasti* (velvetleaf) were more competitive than those from non-mycorrhizal plants when grown together. Seeds from mycorrhizal plants had a higher P concentration as well. This may have implications for organic production where seedling vigour is important for crop competitiveness against weeds – especially as organic farmers are likely to save harvested seed for the following growing season and where P is often the most limiting nutrient in soil.

While plant species may have an effect on AMF colonization, the fungi may also be directly responsible for reducing non-host weed competitiveness with crops. Arbuscular mycorrhizal fungi can have an antagonistic effect on non-host weeds. Francis and Read (1995) found that AMF reduced non-host weed seedling emergence and growth and disrupted morphological development (stunting).

2.3.4 Profitability

In addition to the benefits provided to the crop rotation, field pea and lentil grown as grain legumes have the potential to be profitable for organic producers. Price premiums and markets can fluctuate, and organic production systems require high premiums and crops with high market value to be profitable in the long term (Smith et al., 2004). The crop rotation must include some high-value crops to be competitive with conventional systems, and sometimes may be more profitable (Smith et al., 2004).

In 2005, the average selling price for organic field pea was \$232.89 tonne^{-1} (\$6.34 bu^{-1}) and \$1320.96 tonne^{-1} (\$35.94 bu^{-1}) for lentil (University of Saskatchewan, 2006). The same crops grown conventionally had an average selling price of \$148.77 tonne^{-1} (\$4.05 bu^{-1}) for field pea and \$286.49 tonne^{-1} (\$7.80 bu^{-1}) for lentil (AAFC, 2007a; AAFC, 2007b).

2.4 Problems with Incorporating Grain Legumes into an Organic Crop Rotation

2.4.1 Low competitive ability

The competitive ability of a crop will depend on vegetative growth and ground cover (McDonald, 2003). The competitive ability of a crop stand is important for reducing weed problems (Salonen et al., 2005) and can be determined by a number of factors, including growth habit, weed species present and climate (Boerboom and Young, 1995).

In field pea, plant height was an important determining factor in competitiveness with weeds when testing a number of genotypes (McDonald, 2003). The open canopy produced by semi-leafless pea varieties that are popular for reduced disease incidence decreased the ability of the crop to compete for light with weeds (Wall et al., 1991; Salonen et al., 2005). Yield reductions have reached 40 to 80% due to weed competition (Grevsen, 2003). Similar yield reductions were found by Boerboom and Young (1995) where field pea not treated with herbicide showed yield reductions of 30 to 40% due to weed competition. Despite high yield losses associated with weed competition, field pea is better able to suppress weeds and reduce weed seed production and dispersal than lentil (Mishra et al., 2006)

Similarly, lentil is poorly competitive with weeds (McDonald et al., 2007). The poor competitive ability of lentil is due to its slow growth at early vegetative stages, small stature and small amount of biomass produced (Siddique et al., 1998; Elkoca et al., 2005). For these reasons, weeds can quickly overtake lentil early in the growing season and dominate resource acquisition (Elkoca et al., 2005). Lentil also has a low capacity to compensate, or close the canopy, when the density is not sufficient (Siddique et al., 1998). Lentil yield losses due to weed competition can reach 80% (Boerboom and Young, 1995; Paolini et al., 2003). Boerboom and Young (1995) reported that lentil yield in a weedy plot equaled only 17% of the yield in a hand-weeded plot. The environmental conditions during the growing season were hotter than normal and *Chenopodium album* (common lambsquarters), a highly competitive weed, comprised a large portion of the weed biomass. In a lentil seeding rate study conducted by Paolini et al. (2003), yield losses due to weed infestation reached 80% at the lowest seeding rate of 125 plants m^{-2}, which is similar to the recommended rate for conventional production of lentil in western Canada (Saskatchewan Pulse Growers, 2000).

2.4.2 Insufficient nutrient input

Organic systems are largely dependent on soil processes for nutrient cycling, and the dominant method of nutrient addition to organic grain farms is through incorporation of crop residues (Stockdale et al., 2002). The type of crop residue added will have an impact on the nutrient availability for following crops.

Grain legumes supply less N for the following crop than legumes grown as a green manure (Watson et al., 2002a) or summerfallow (Badaruddin and Meyer, 1994).

More N was available with legumes grown as green manure than for grain (Brandt, 1996), and plant-available nitrate was lower in spring when lentil was grown than when the land was under summerfallow (Badaruddin and Meyer, 1994). Growing grain legumes organically may result in a negative N balance (Haynes et al., 1993; Carranca et al., 1999). Haynes et al. (1993) found that both field pea and lentil fixed less N than was removed in the grain. However, the researchers noted that while the N balance was negative, there was more N in the legume residue than in that of non-leguminous crops.

In Saskatchewan, where water is often the limiting factor to agricultural production, reduced soil water storage can have an impact on soil microorganisms that mobilize nutrients (Campbell et al., 1992). Nitrogen fixation by *Rhizobium* species is highly dependent on soil water content – drought conditions result in little N_2 fixation (Carranca et al., 1999). Microorganisms are also important for the mobilization of organic P in soil (Smith and Read, 1997; Havlin et al., 1999); however, the amount of P returned to the soil after a grain legume crop is also an important consideration in determining the P balance of organic systems. There is greater loss of P with grain removal than when green manure legumes are grown. A study by Selles et al. (1995) found that 72% of the total P taken up by the crop, or 3.65 kg P ha^{-1}, was removed as lentil grain. This is an indication that the incorporation of grain legumes into an organic crop rotation will result in a reduction in soil P over time.

2.4.3 Soil water usage

Organically-managed land has been shown to have higher moisture levels than land managed conventionally (Reganold et al., 1987). This is likely due to higher water-capturing and water-holding capacity of soils from increased organic matter rather than lower water usage by organic crops (Reganold et al., 1987; Lotter et al., 2003). Reganold et al. (1987) compared legume-based organic and conventional fields in Washington State and found that organic matter and water-holding capacity was higher on the organic farm. The higher organic matter levels were attributed to the loss of topsoil from the conventional farm (water erosion of 32.4 ton ha^{-1} yr^{-1}). A study performed in Pennsylvania also found that the water-holding capacity was higher in a legume-based organic system than a conventional system (13% and 30% higher in consecutive years) (Lotter et al., 2003). Despite some evidence that organically-managed soils may hold more water than conventionally-managed soils, plant-available moisture as well as other soil qualities are continuous concerns for Saskatchewan farmers (Campbell et al., 1992; Weinhold and Halvorson, 1998), especially since organic farmers use tillage as an important method of weed management and must draw on other ways to conserve soil water (SOD, 2000; Mohler, 2001). The main method used by organic farmers to increase soil water is by summerfallow, where the land is periodically tilled to manage weeds, but no crop is grown; however, summerfallow leads to erosion, reduced organic matter and reduced soil fertility (Biederbeck and Bouman, 1994; SOD, 2000). A potential replacement for summerfallow is the use of green manure crops (SOD, 2000). Saskatchewan studies have found green manure reduced soil water to be slightly lowe (Brandt, 1996) or significantly lower than summerfallow (Townley-Smith et al., 1993; Biederbeck and Bouman, 1994). Green manure crops may use less water than grain legumes. Dry pea in North Dakota used 26.6 cm of water when harvested for grain, but only 10.4 cm when harvested for forage (Anderson et al., 2003). Brandt (1996) found that there was more soil water available after growing green manure legumes than grain legumes.

2.5 Recommended Seeding Rates

The recommended seeding rates for organic production of field pea and lentil have not been established for western Canada. As a result, organic producers are reliant upon seeding rates determined for conventional production of these crops. These seeding rates are appropriate for use along with fertilizers and pesticides, but may not be the optimal seeding rates for organic production where crop competitive ability is important for weed control. Optimal seeding rates for field pea and lentil may also be dependent on the cost of seed; higher costs for organic seed may be prohibitive to increasing seeding rates beyond a certain level (Siddique et al., 1998).

2.5.1 Field pea

The recommended rate for conventional production of field pea in western Canada is 88 plants m^{-2} (Saskatchewan Pulse Growers, 2000). Seeding rates for organic production have not been determined, however, researchers in other countries have determined that higher seeding rates were important for organic production systems. A Danish study recommended seeding field pea as high as is economically possible (up to 150 plants m^{-2}) to obtain favourable yields and suppress weeds (Grevsen, 2003). Bond and Grundy (2001), however, warn that lower fertility in organic systems may limit the producer's ability to increase seeding rates for weed suppression. A conventional study in western Canada found that seeding rates greater than the recommended rate (up to 100 plants m^{-2}) were beneficial, especially when weed control was not optimal (Johnston et al., 2002).

Increasing crop density increases the competitive ability of field pea with weeds (Wall et al., 1991). An increase in field pea density decreased the number of weed seeds per plant when grown with wild onion (Mishra et al., 2006). Mishra et al. (2006) also found that field pea was a better competitor with weeds than lentil regardless of density.

2.5.2 Lentil

The recommended seeding rate for conventional production of lentil in western Canada is 130 plants m^{-2} (Saskatchewan Pulse Growers, 2000). An unpublished study conducted at a single site in Saskatchewan determined that the optimal seeding rate for organic production of lentil is 195 to 260 plants m^{-2} and that row spacing should be narrow to allow for better crop competition with weeds for resources (Johnson, 2002). Where row spacing was held constant, European studies have determined that optimal seeding rates should exceed 130 plants m^{-2} where pesticides are not used, although many of the experiments were not conducted as organic production systems. In an Italian study, the optimal plant density for lentil when using mechanical weed control was determined to be between 177 to 250 plants m^{-2} (Paolini et al., 2003). The authors suggested, however, that weed control by tillage managed early-emerging weeds but allowed for late-emerging weeds to flourish later in the season, and that weed populations may not be reduced (Paolini et al., 2003). Similarly, Ball et al. (1997) found that increasing small-seeded lentil seeding rates had a suppressive effect on weed dry weight in the eastern United States. In an Australian field study, lentil showed a strong response to seeding rate; increased rates increased lentil yield and decreased weed biomass up to 200 plants m^{-2} (McDonald et al., 2007). Another Australian study suggested a seeding rate of 150 plants m^{-2}, but up to 230 plants m^{-2} where growing conditions were less favourable (Siddique et al., 1998). In a Turkish study, lentil was seeded at a rate of 350 plants m^{-2}, which produced a plant density of 200 to 226 plants m^{-2}. Yield loss due to weed interference was approximately 50% as compared to a hand-weeded check (Elkoca et al., 2005). A common theme throughout these seeding rate studies is that seeding rates should exceed the recommended rate for conventional production in western Canada.

Although many studies have found a link between increased seeding rate and decreased weed density, this is not always the case. Boerboom and Young (1995) found no decrease in weed density when increasing the seeding rate of field pea and lentil 50% above the recommended rate.

3. EFFECT OF SEEDING RATE ON YIELD, WEED ABUNDANCE AND SOIL AND CROP NUTRIENTS IN ORGANIC FIELD PEA AND LENTIL

3.1 Introduction

Since seeding rates for organic production of field pea and lentil have not been established for western Canada, organic producers must rely on seeding rates determined for conventional production of these crops. Conventional crop production practices rely heavily on pesticides to control weeds and synthetic fertilizers to maintain soil fertility. In contrast, organic cropping systems rely on cultural and mechanical methods to manage weeds and legumes to maintain soil fertility. Because these production systems are very different, seeding rates established for conventional production may not be suitable for organic systems.

Legumes are an important part of organic systems, especially when animal manure is not applied. Legumes, such as field pea and lentil, require less soil N as they can utilize biologically fixed N_2 when grown in association with rhizobia. Organic field pea can derive up to 60% of its N requirement through atmospheric N_2 fixation (Corre-Hellou and Crozat, 2005), while lentil can derive up to 75% of its N requirement through N_2 fixation (Bremer et al., 1990; Schmidtke et al., 2004). Organic field pea and lentil also have high premiums associated with their production as grain legumes (University of Saskatchewan, 2006) and thus may be attractive options for production in organic systems.

While there are many benefits to growing field pea and lentil in organic systems, these crops are poorly competitive with weeds and may experience yield losses of up to 80% (Boerboom and Young, 1995; Grevsen et al., 2003; Paolini et al., 2003). Increasing the seeding rate of these crops may increase their competitive ability and decrease weed abundance. Increasing seeding rates in many instances increases yield and competitiveness of the crop (Wall et al., 1991; Mohler, 2001); however, the effects on soil fertility, seed quality and water use efficiency (WUE) are varied or unknown. Most seeding rate studies focus solely on how either yield or crop competitiveness changes with increasing crop density. There are few studies that have determined the effects of seeding rate on many aspects of the production system. The objectives of this experiment were to determine how seeding rate affects a number of factors, including crop yield, weed abundance and soil fertility.

3.2 Materials and Methods

3.2.1 2005 field experiment

3.2.1.1 Site description

Two locations were chosen on pre-existing organic farms in 2005. The locations were south of Vonda, SK and west of Delisle, SK. The sites were managed organically for approximately 20 and 8 y, respectively. Locations are given in Table 3.1. Both sites were seeded onto barley stubble.

Precipitation and temperature data were recorded during the growing season by weather stations in close proximity to the research plots. Soil samples for nutrient status and moisture content were taken with a 5cm soil corer prior to seeding, at depth increments of 0 to 15 cm, 15 to 30 cm, 30 to 60 cm and 60 to 120 cm at three random locations within the trial area. These samples were measured for bulk density by determining the volume of each sample from the inner diameter of the core (5 cm diameter), then weighing the sample before and after drying at 105˚C for 2 d to remove soil water.

Gravimetric soil water measurements were made using the weights before and after drying, and volumetric soil water was determined by multiplying the bulk density and gravimetric soil water measurements. Soil samples were also taken at depths of 0 to 15 cm and 15 to 30 cm at five random locations within each trial area. Samples from each depth were bulked and sent to ALS Laboratory Group (Saskatoon, SK.) for pH, cation exchange capacity (CEC), and macronutrient analysis (Table 3.1).

Table 3.1 Locations and soil characteristics in the upper 15 cm of the soil profile of trial sites in central Saskatchewan in 2005 and 2006.

	2005		2006	
Site	Vonda	Delisle	Vonda	Vanscoy
Location	52°18'25"N 106°06'03" W	51°49'31"N 107°19'01"W	52°17'50"N 106°06'05"W	51°57'24"N 106°56'44"W
Soil Association	Oxbow	Elstow	Oxbow	Asquith
Soil zone	Black	Dark Brown	Black	Dark Brown
Soil texture	Clay loam	Loam	Clay loam	Clay loam
pH	8.4	7.2	8.2	6.3
E.C. (mS cm^{-1})	0.2	0.3	0.2	0.2
Soil test N (µg g^{-1})	9.4	12.5	7.2	5.6
Soil test P (µg g^{-1})	6.7	12	3.3	>30

3.2.1.2 Soil analysis

Two soil samples were taken after harvest in each plot in randomly selected locations at depths of 0 to 15 cm and 15 to 30 cm and samples at each depth were bulked within each plot. Each bulked sample was subsampled and assessed for gravimetric soil water as described above. The remaining samples were air-dried and ground to pass through a 2 mm sieve. Subsamples of the ground soils were analyzed for total percent N using a Leco CNS-2000 (LECO Corporation, St. Joseph, MI, USA) furnace at 1100˚C. Subsamples were taken for determination of available phosphate-P for the 0- to 15-cm depth using the modified Kelowna extraction method (Qian et al., 1994) and inorganic N (NH_4^+ + NO_3^-) by KCL extraction for both the 0- to 15-cm and 15- to 30-cm depths (Maynard and Kalra, 1993) by ALS Laboratory Group (Saskatoon, SK).

3.2.1.3 Experimental design and plot management

In each location, field pea (*Pisum sativum* cv CDC Mozart) and lentil (*Lens culinaris* cv CDC Sovereign) were seeded at a 20 cm row spacing 2.5 cm deep using a cone seeder with an offset disc drill to achieve five target plant densities for each crop: 10, 25, 62, 156 and 250 plants m^{-2} and 15, 38, 94, 235 and 375 plants m^{-2} respectively. The number of seeds planted was increased based on the percentage germination to achieve target plant densities. The germination test was performed by placing 100 seeds on moist paper towel stored in the dark for 7 d, then determining the number of seeds germinated. When seeding, Nodulator® granular *Rhizobium* inoculant for pea and lentil (Becker Underwood, Saskatoon, SK) was placed with the seed at the recommended rate. The natural weed population was used in this study, as the population was relatively homogeneous.

One green manure and one summerfallow treatment were included in the treatments for each crop. For green manure treatments, Indianhead lentil were seeded at a density of 235 plants m^{-2} and Trapper field pea were seeded at a density of 62 plants m^{-2} according to Lawley (2004). Each site was set up in a randomized complete block design with four replicates and a single plot size of 2m x 6m.

Growing degree days were determined using the equation from Bullied et al. (2006):

$$GDD_{daily} = \left(\left[T_{\max} + T_{\min}\right]/2\right) - T_{base} \text{ , and} \qquad [3.1]$$

$$GDD = \sum_{i=1}^{n} GDD_{daily}$$

where GDD_{daily} is the daily number of growing degree days, T_{max} is the maximum temperature (in degrees Celsius) reached each day, T_{min} is the minimum temperature recorded and T_{base} is the base temperature (5˚C), or the minimum temperature required for crop growth. GDD is the sum of daily growing degree days, and *n* is the number of days passed since seeding.

In-crop harrowing was performed with two passes using a tine harrow 26 d after planting (DAP) (183 GDD) in Vonda and 33 DAP (300 GDD) in Delisle, as well as tillage (two passes using a tandem disc) in the summerfallow treatment 56 DAP (485 GDD) in Vonda and 47 DAP (436 GDD) in Delisle.

Actual crop and weed species densities were determined by counting the number of each species in two randomly selected 0.25 m^2 quadrats in each plot after the in-crop harrowing was performed.

Prior to the green manure ploughdown, a wild mustard (*Sinapis arvensis*) infestation was hand-weeded in Delisle. The heavy infestation occurred on one side of the plot area. Because the infestation was not spatially homogeneous throughout the trial and the farm owner objected to its presence, the wild mustard was removed. Wild mustard did not occur at any other location within the lentil or field pea trials at Delisle.

The optimal crop stage for the green manure ploughdown is the early bud stage (Lawley, 2004); however, the green manure ploughdown occurred 61 DAP (588 GDD or late flowering stage) at Vonda and 53 DAP (523 GDD or mid-flowering stage) at Delisle. The difference in crop stage at ploughdown between the optimal and actual stage was due to inclement weather that resulted in delays at both sites. The ploughdown was performed in two passes using a tandem disc. A second tillage pass was performed 113 DAP (1121 GDD) at Vonda and 104 DAP (1072 GDD) at Delisle for both the summerfallow and green manure treatments.

Aerial biomass sampling of both crop and weeds occurred at physiological maturity (i.e., the crop was ready to be swathed), which was indicated by yellow pods for field pea and tan pods that rattled when shaken for lentil (Saskatchewan Pulse Growers, 2000). Sampling at Vonda occurred 89 DAP (898 GDD) and 82 DAP (863 GDD) at Delisle. Plant material was separated into crop, broadleaf weed species and grassy weed species. All plant material was dried at 60˚C for 72 h and then weighed to determine biomass.

A hand harvest of four 1-m long rows (equivalent to 0.81 m^2) of crop in each plot occurred at 103 DAP (1003 GDD) in Vonda and 94 DAP (954 GDD) in Delisle for the pea and first two replications of lentil. Maturity was delayed slightly in replications three and four for the lentil trial at Delisle and were harvested at a later date, 120 DAP (1121 GDD).

3.2.2 2006 field experiment

3.2.2.1 Site description

In 2006, two sites were chosen near Vonda, SK and Vanscoy, SK. Legal land locations are given in Table 3.1. Crops were seeded onto wheat stubble at both sites. Bulk density and soil moisture sampling was performed May 18 at both sites, as well as bulk density at the 2005 site at Vonda (Section 3.2.1.1).

3.2.2.2 Experimental design and plot management

The design was similar to 2005 with a few modifications. Individual plot size was increased to 4 m wide and 6 m long to allow for an undisturbed 2 m strip for mechanical harvest. One additional treatment was added for the 2006 growing season – a higher seeding rate for each green manure treatment. This modification was made due to poor crop emergence in all green manure plots in 2005. The intent to include a higher seeding rate green manure treatment was to achieve the target plant density. The lentil green manure seeding rate was increased to 375 plants m^{-2}, and the field pea seeding rate to 156 plants m^{-2}.

Plots were managed as described in Table 3.2. A Canada thistle (*Cirsium arvense*) infestation was hand-weeded prior to the green manure ploughdown in the

Table 3.2 Days after planting (DAP) and growing degree days (GDD) for plot management of organic field pea and lentil in 2006 at sites in central Saskatchewan

	Vonda				Vanscoy			
	Field pea		Lentil		Field pea		Lentil	
Operation	DAP	GDD	DAP	GDD	DAP	GDD	DAP	GDD
Seeding	May 18		May 18		May 12		May 16	
In-crop harrow	13	151	13	151	21	200	15	174
Summerfallow tillage	49	530	49	530	47	476	43	450
Ploughdown	51	564	51	564	54	579	50	553
Summerfallow tillage	79	967	79	967	84	1016	80	990
Physiological maturity	72	882	79	967	77	919	83	969
Hand harvest	83	1039	92	1155	83	1004	85	1062
Mechanical harvest	97	1224	97	1224	96	1177	92	1161

field pea trial at Vonda, as the occurrence of the weed was not homogeneous throughout the trial and the extremely competitive nature of Canada thistle may have strongly influenced results where it occurred within plots. A mechanical harvest of 1.5m x 6m was performed in the previously-mentioned undisturbed 2m strip. The first replication of field pea and lentil at Vonda experienced saturated soil conditions for a prolonged period, and were not included in the analysis.

3.2.3 Plant analysis

Aerial biomass sampled at harvest was air-dried in a covered outdoor facility in cloth bags for one week, then moved indoors and dried further in a heated facility at approximately 30˚C. Samples were stored indoors until threshing. Samples were weighed prior to threshing, and then threshed by machine.

Water use efficiency (WUE) was determined from soil water storage determined prior to seeding and total precipitation during the growing season. The equation used was adapted from Zentner et al. (2001):

$$WUE = Y_{grain} / [PT + (\theta_s - \theta_h)] \qquad [3.2]$$

where Y_{grain}= grain yield (kg ha^{-1}), PT = growing season precipitation (mm), θ_s = water storage in spring (mm) and θ_h = water storage at harvest (mm).

Seed weight was determined from the cleaned, threshed seed weight, and vegetative weight was determined by subtracting seed weight from the total biomass sample weight. Seed quality was assessed using the Canadian Grain Commission's seed grading guides for field pea and lentil (CGC 2005a; CGC 2005b). A further assessment of seed quality using 100 seed weight was also performed. Two samples of 100 seeds were weighed and averaged for each plot.

Incidence of disease was a concern for denser stands, so grain samples from the highest seeding rates of both field pea and lentil were tested for seed-borne disease. Fifty seeds from each replicate were surface sterilized with a 10% bleach solution for two min, then plated using sterile technique onto potato-dextrose agar (10 seeds per Petri dish) and set onto lighted benches for one week (Morrall and Beauchamp, 1988). Assessments of occurrence of disease were made by a plant pathology technician based on the colour and morphology of the colonies observed.

Once seed quality and disease incidence were assessed, seed and straw samples were ground and stored for nutrient analysis. Both seed and straw samples were assessed for P content by performing an acid digestion (Thomas et al., 1967). Phosphorus levels in the digested samples were determined colorimetrically using a Technicon AutoAnalyzer II (Technicon Industrial Systems, Tarrytown, N.J.).

3.2.4 Statistical analysis

Data were analyzed using the PROC MIXED procedure of SAS (SAS Institute Inc., 2004) with block and site-year as random effects. Treatment effects were considered significant at $P \leq 0.05$. Data were transformed to meet the assumption of homogeneity of variance. The transformations used are listed in Table 3.3. For each crop, sites and years were combined as there were no significant interactions between site-year and treatment. A non-linear regression model was fitted to the crop biomass means using the PROC NLIN procedure of SAS (SAS Institute Inc., 2004). The two-parameter Michaelis-Menten model, primarily used to describe enzyme kinetics, was used with a modification of parameters:

$$Y = Y_{\max} \times D / (D_{50} + D) \qquad [3.3]$$

where Y_{max} (kg ha^{-1}) is the maximum yield as the density approaches infinity, D_{50} (plants m^{-2}) is the crop density at which half of Y_{max} occurs, and D (plants m^{-2}) is seeding rate. This model was chosen to describe the data because it provided a good fit to the data and biologically meaningful parameters.

The relationship between weed biomass and crop density was described using a modified version of the Michaelis-Menten equation to fit decreasing rather than increasing biomass:

$$Y = Y_{\max} - Y_{\max} \times D / (D_{50} + D) \qquad [3.4]$$

where Y_{max} (kg ha^{-1}) is the maximum yield as the density approaches infinity, D_{50} (plants m^{-2}) is the crop density at which half of Y_{max} occurs, and D (plants m^{-2}) is seeding rate. Both forms of the Michaelis-Menten equation were fitted to the resulting means for each seeding rate from the mixed model ANOVA (Table A.1, A.2, A.3). The fit of the equation to the means was determined using the adjusted R^2 value in SigmaPlot 10.0 (Systat Software, Inc.).

Table 3.3 Transformations used for organically-grown field pea and lentil datasets combined for sites and years in central Saskatchewan in 2005 and 2006 to satisfy the assumption of homogeneity of variance for PROC MIXED in SAS.

Variable	Field pea	Lentil
Emergence	Ln[†]	Ln
Crop biomass	√[‡]	√
Weed biomass	Ln	Ln
Proportion of broadleaf weeds	Arcsine[§]	Arcsine
Weed number	None	None
Yield (hand-harvest)	√	√
Yield (mechanical harvest)	None	None
Harvest index	None	None
Hundred seed weight	None	None
Profit	√	√
Percent AMF colonization	Arcsine	Arcsine
Water use efficiency	None	None
Seed P concentration	None	None
Straw P concentration	None	Ln
Seed P:Straw P ratio	None	None
Straw P uptake	√	√
Seed P uptake	√	√
Percent soil N (all depths)	Arcsine	Arcsine

[†] Natural log transformation
[‡] Square root transformation
[§]Arcsine transformations were used for percentage data

3.3 Results

3.3.1 Weather

Climatic conditions varied between years and from the 30 y average for the Saskatoon area. There was considerable precipitation and higher mean temperatures for both years, especially during the month of June (Table 3.4).

3.3.2 Effect of field pea seeding rate

3.3.2.1 Emergence

Emergence rates ranged from 52% to 66%. Low emergence rates resulted in lower plant densities than intended (Table 3.5). There was no trend in emergence with increasing seeding rate.

3.3.2.2 Crop and weed biomass

Field pea biomass at physiological maturity increased asymptotically with increasing seeding rate (Fig. 3.1). Biomass increased from 602 to 4695 kg ha^{-1} between 10 and 250 plants m^{-2}. One half of the predicted maximum biomass yield was reached at a seeding rate of 110 plants m^{-2} (Table 3.6).

As crop density increased, weed biomass abundance decreased (Fig. 3.1). Weed biomass was decreased by half at 92 plants m^{-2}, the same seeding rate at which grain yield reached half of the predicted maximum (Table 3.6). Total weed numbers did not decrease significantly with increasing seeding rate (Table 3.7).

Table 3.4 Climatic data for sites in central Saskatchewan for seeding rate studies of organically-produced field pea and lentil in 2005 and 2006.

Month	Precipitation (mm)				
	30 y average†	2005		2006‡	
		Vonda§	Delisle¶	Vonda	Vanscoy
May	20	39	29	62	47
June	44	137	171	85	107
July	63	38	44	67	40
August	58	92	54	47	38
Total	185	306	298	261	232

	Mean daily temperature (˚C)				
	30 y average	2005		2006	
		Vonda	Delisle	Vonda	Vanscoy
May	11.5	10.4	10.8	12.0	12.5
June	16.0	14.8	15.3	16.5	15.5
July	18.2	17.9	18.9	18.9	19.8
August	17.3	15.5	16.4	17.9	17.5

† Based on Saskatoon weather data from 1971-2000 from Environment Canada

‡ 2006 precipitation data gathered from nearest Environment Canada weather stations

§ Vonda 2005 climate data from nearest Environment Canada weather station (Osler, SK.)

¶ Delisle 2005 climate data from nearest Environment Canada weather station (Saskatoon, SK.)

Table 3.5 Emergence of organic field pea combined for sites in central Saskatchewan in 2005-06.

Seeding rate	Emergence	
Viable seeds m^{-2}	plants m^{-2}	%
10	6	60*bc*†
25	13	52*c*
62	41	66*a*
156	102	65*b*
250	146	58*bc*

†Means followed by the same letter are not significantly different at $P \leq 0.05$ according to the least squares means test.

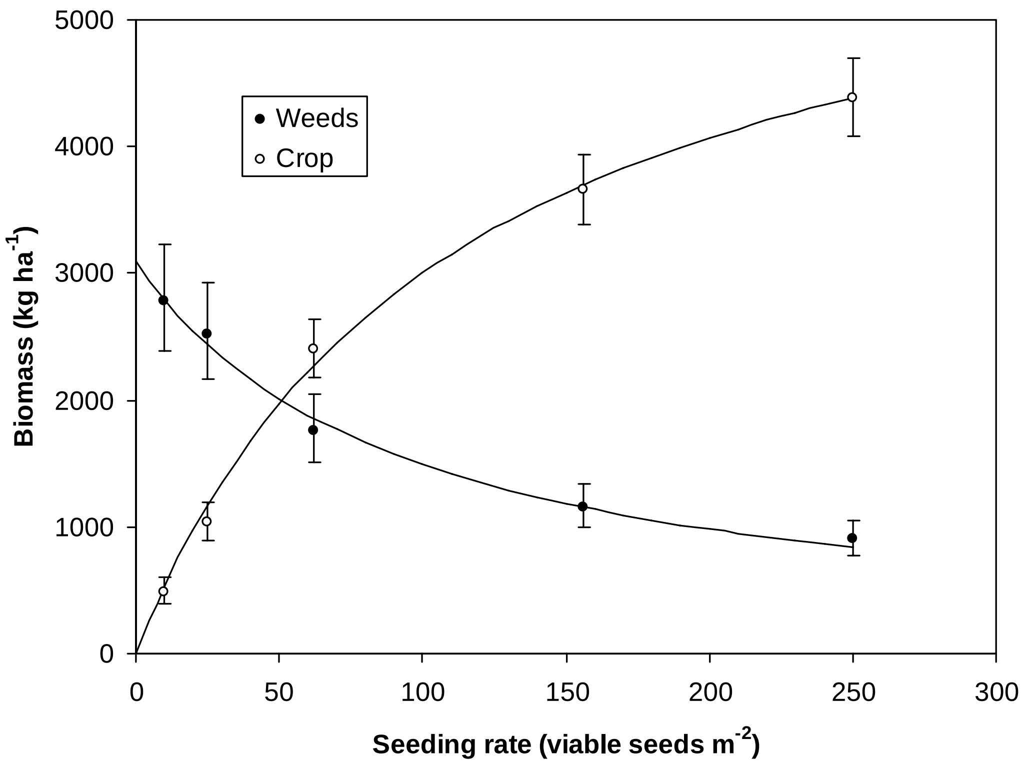

Fig. 3.1 Organically-grown field pea crop and weed biomass at physiological maturity. Data were combined between sites and years in central Saskatchewan for 2005 and 2006. Bars indicate one standard error of the mean.

Table 3.6 Parameter estimates (±S.E.) for organic field pea crop and weed biomass non-linear regressions based on equations 3.3 and 3.4, respectively. Data combined for sites in central Saskatchewan in 2005 and 2006.

	Parameter estimates		
Variable	Y_{max}[†]	D_{50}[‡]	R^2
Crop biomass	6326 (351)[§]	110 (14)	0.99
Weed biomass	3101 (99)	92 (10)	0.99
Grain yield	2353 (61)	92 (6)	0.99

[†]Y_{max} is the maximum yield

[‡]D_{50} is the density at which one-half of Y_{max} is achieved

[§]± standard error in parentheses

Table 3.7 Total number of weeds and proportion of broadleaved weeds in organically grown field pea combined between sites in central Saskatchewan in 2005 and 2006.

Seeding rate	Weed number	Proportion of broadleaved weeds
viable seeds m^{-2}	weeds m^{-2}	%
10	275	81
25	217	83
62	191	80
156	191	83
250	209	82
Diff. of LS means†	NS‡	NS

†Differences between least squares means
‡Not significant at $P \leq 0.05$

Broadleaved weeds were abundant in the field pea trials at all locations and all years. The most common species found, combined for all sites in 2005 and 2006, included *Sinapis arvensis* (wild mustard), *Chenopodium album* (lambsquarters), and *Polygonum convolvulus* (wild buckwheat). The most common grassy weeds for both crops were *Avena fatua* (wild oat), *Setaria viridis* (green foxtail), *Hordeum vulgare* (volunteer barley), and *Triticum aestivum* (volunteer wheat). The mean proportion of broadleaf weed biomass for all seeding rates ranged from 80 to 83% (Table 3.7). There were no significant differences for proportion of broadleaf weed biomass between treatments.

3.3.2.3 Grain yield

Field pea seed yield showed a similar trend to crop biomass, increasing asymptotically to the highest seeding rate (Fig. 3.2). Yield increased from 209 to 1725 kg ha^{-1} between 10 and 250 plants m^{-2}. Half of the maximum predicted seed yield was reached at a seeding rate of 92 plants m^{-2}, approximately 20 plants m^{-2} lower than the crop biomass (Table 3.6). Grain yield is likely to reach a maximum more quickly than plant biomass, therefore excess biomass may be produced at higher crop densities rather than a consistent increase in both crop biomass and grain yield.

When comparing seed yields from mechanical and hand-harvested samples, the hand-harvested sample was consistently higher than the sample taken by plot combine (Table 3.8).

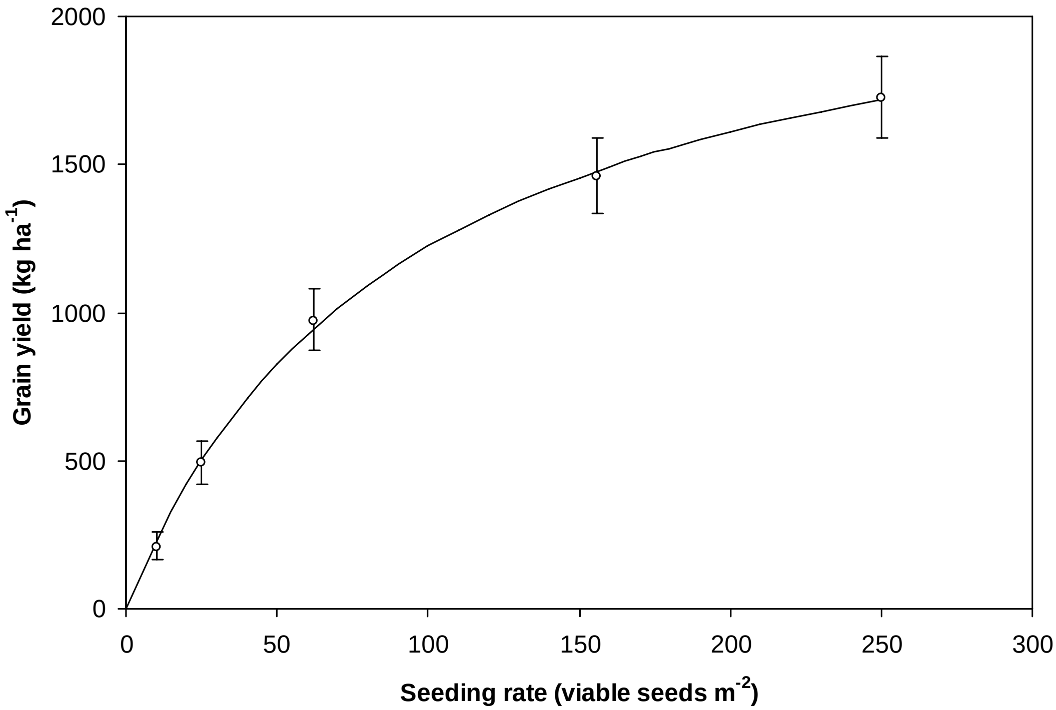

Fig. 3.2 Impact of seeding rate on grain yield of organically grown field pea. Data represent combined sites analyses for four sites and two years (Vonda and Delisle in 2005, and Vonda and Vanscoy in 2006). Bars indicate one standard error of the mean.

Table 3.8 Yield components for organically-grown field pea combined between sites in central Saskatchewan in 2005 and 2006.

Seeding rate	Harvest index	WUE	100 Seed wt	Hand-harvested yield	Mechanical yield
(viable seeds m^{-2})	(seed:seed+straw)	(kg ha^{-1} mm^{-1})	(g 100 $seeds^{-1}$)	(kg ha^{-1})	(kg ha^{-1})
10	0.48*a*†	0.66*e*	20.6	209	132
25	0.47*ab*	1.58*de*	20.6	491	379
62	0.48*a*	3.18*c*	20.4	973	590
156	0.47*a*	5.17*b*	20.7	1460	1136
250	0.44*b*	6.93*a*	20.7	1725	1621
Diff. of LS means‡			NS§		

† Means followed by the same letter within columns are not significantly different at $P \leq 0.05$ according to pairwise comparisons of least squares means
‡Difference of least squares means
§ Not significantly different within columns at $P \leq 0.05$

3.3.2.4 Yield and seed quality components

Harvest index values provided further evidence that less grain was produced per kg of aerial biomass. Harvest index did not change between seeding rates except a decrease at the highest seeding rate from 0.47 to 0.44 (Table 3.8), indicating that more vegetative biomass was produced at the highest crop density than any other.

Water use efficiency (WUE) increased as seeding rate increased. Soil water storage measured to a depth of 30 cm did not change between treatments and so the greater the grain yield, the higher the WUE (Table 3.8).

Hundred seed weights did not change significantly between crop densities, indicating that seed quality was maintained (Table 3.8). Visual inspection of seed samples from all seeding rates indicated that there was no trend in seed grade between seeding rates, and all samples in 2005 and 2006 met the Canadian Grain Commission (CGC) standards of ‘Grade 1’.

An assessment of seed-borne disease for the highest seeding rate determined that incidence of disease was rare and not an issue in either year or site (Stephanie Boechler, personal communication). The most common disease-causing agent found was *Alternaria* with 2.4% of seeds tested infected in field pea (Table 3.9).

Seed and straw P concentrations did not change significantly between seeding rates, and so the pattern for P uptake closely followed that of yield (Table 3.10). Although not statistically significant, straw P concentration showed a tendency to increase as seeding rate increased (Table 3.10). As a result, the ratio of seed P:straw P decreased slightly at higher seeding rates but the difference was not statistically significant (Table 3.10).

Table 3.9 Percent incidence of various seed-borne disease-causing agents at the highest seeding rate for organic field pea (250 plants m^{-2}) combined for sites in central Saskatchewan in 2005 and 2006.

Crop	*Alternaria*	*Fusarium*	*Ascochyta*	*Mycosphaerella*	*Stemphylium*	*Botrytis*
Pea	2.4	1.1	n/a	0.1	0.2	0.2

Table 3.10 Seed and straw P uptake and concentration after harvest for organically grown field pea combined between sites in central Saskatchewan for 2005 and 2006

Seeding rate	Seed P uptake	Straw P uptake	Seed P conc.	Straw P conc.	Ratio
(viable seeds m^{-2})	(kg ha^{-1})	(kg ha^{-1})	(mg kg^{-1})	(mg kg^{-1})	(seed P:straw P)
10	0.5*d*	0.2*c*	2307	652	3.5
25	1.1*c*	0.3*c*	2236	605	3.7
62	2.1*b*	0.9*b*	2209	635	3.5
156	3.2*ab*	1.6*ab*	2187	744	2.9
250	3.8*a*	2.7*a*	2218	726	3.1
Diff. of LS means†			NS ‡	NS	NS

†Differences between least squares means

‡Not significantly different within columns at $P \leq 0.05$

3.3.2.5 Soil nutrients at harvest

Available P remaining in the soil after harvest varied between sites, but differences within sites were small (Table 3.11). Significant differences ($P \leq 0.05$) were detected only at Vanscoy in 2006. This site exhibited the highest available soil P at seeding rates of 10, 25 and 63 plants m^{-2}, and the lowest soil P at 156 plants m^{-2}, although differences were slight between the lowest and highest values (0.3 $\mu g\ g^{-1}$) (Table 3.11). When available soil P concentrations were compared with spring test results, all sites showed a decrease in available soil P at harvest (Table 3.1; 3.11).

Total percent N in soil also showed little variation within sites, and the only significant differences ($P \leq 0.05$) were in Vonda in 2006. The highest seeding rate (250 plants m^{-2}) had the highest percent soil N, but was not significantly different from any other treatment except the lowest seeding rate for green manure and the second highest seeding rate (156 plants m^{-2}), which exhibited the lowest percent soil N, although the differences between the means were small (1 to 2%) (Table 3.11).

Measurable changes occurred in soil inorganic N ($NH_4^+ + NO_3^-$) between treatments (Table 3.11). Trends were similar between sites, with the highest inorganic N in the summerfallow and green manure treatments. This trend was evident in both the 0- to 15-cm and 15- to 30-cm depths (Table 3.11) and was significant at most sites. The lowest concentrations of soil inorganic N were generally found at the lowest three seeding rates, although differences were not significant at most sites. In many cases, inorganic N increased at the highest seeding rates as compared to the lower rates. For example, at Delisle in 2005, inorganic N ranged from 10.7 to 11.0 $\mu g\ g^{-1}$ between the three lowest seeding rates and increased to 14.1 and 12.3 $\mu g\ g^{-1}$ at 156 and 250 plants m^{-2} in the top 15 cm, respectively, although the differences were not found to be significantly different with the least squares means test (Table 3.11). While the data may have suggested a trend towards increasing inorganic N levels at higher seeding rates, levels were generally lower for seeding rate treatments than the summerfallow and green manure treatments.

At Delisle in 2005, inorganic N was 7 $\mu g\ g^{-1}$ higher in the summerfallow and green manure treatment than the 10, 25, and 63 plants m^{-2} seeding rates, but not significantly higher than the 156 plants m^{-2} seeding rate (Table 3.11).

Table 3.11 Soil nutrient availability after harvest for organic field pea combined for sites in central Saskatchewan in 2005 and 2006.

Seeding rate	Available P	Total N	Inorganic N	
(viable seeds m^{-2})	($\mu g\ g^{-1}$)	(%)	($\mu g\ g^{-1}$)	
Delisle 2005	0-15cm	0-30cm	0-15cm	15-30cm
Summerfallow	2.9	0.21	17.1*a*[†]	18.1*a*
Green manure	2.8	0.22	17.0*a*	17.9*a*
10	2.9	0.21	10.7*b*	8.5*b*
25	2.8	0.22	10.9*b*	9.3*b*
63	3.0	0.22	11.0*b*	9.3*b*
156	2.8	0.23	14.1*ab*	10.6*b*
250	2.8	0.21	12.3*b*	10.7*b*
Diff. of LS means[‡]	NS[§]	NS		
Vonda 2005				
Summerfallow	2.4	0.15	8.9	7.2*c*
Green manure	2.4	0.15	9.7	10.4*a*
10	2.3	0.16	8.8	7.9*bc*
25	2.5	0.16	8.9	8.4*b*
63	2.5	0.15	8.9	8.4*b*
156	2.6	0.15	9.9	9.0*b*
250	2.3	0.14	10.6	8.3*b*
Diff. of LS means	NS	NS	NS	
Vanscoy 2006				
Summerfallow	4.1*ab*	0.23	18.8*a*	12.2*a*
Green manure	4.0*ab*	0.23	17.1*a*	10.8*ab*
Green manure (2x)	4.0*ab*	0.22	19.4*a*	11.0*a*
10	4.2*a*	0.24	6.2*d*	5.5*d*
25	4.2*ab*	0.23	6.5*cd*	4.4*d*
63	4.2*a*	0.25	6.9*bcd*	5.9*c*
156	3.9*b*	0.22	8.3*c*	5.7*c*
250	4.0*ab*	0.24	8.0*cd*	6.3*c*
Diff. of LS means		NS		
Vonda 2006				
Summerfallow	1.5	0.13*ab*	13.1*a*	7.6*a*
Green manure	1.5	0.12*b*	9.8*b*	7.7*a*
Green manure (2x)	1.7	0.13*ab*	9.5*b*	5.1*bc*
10	1.5	0.13*ab*	4.5*c*	4.6*bc*
25	1.7	0.14*ab*	4.6*c*	4.5*bc*
63	1.6	0.13*ab*	4.8*c*	4.8*bc*
156	1.5	0.13*b*	4.4*c*	4.3*bc*
250	1.5	0.14*a*	5.0*c*	5.6*b*
Diff. of LS means	NS			

[†] Means followed by the same letter within columns are not significantly different at $P \leq 0.05$

[‡] Differences between least squares means

[§] Not significantly different within sites and columns at $P \leq 0.05$

At Vonda, the second trial location in 2005, trends were less clear. There were no significant differences at $P \leq 0.05$ at the 0- to 15-cm depth, but some differences were discovered at a depth of 15 to 30 cm. The green manure treatment had a significantly higher concentration of inorganic N (i.e., 10.4 $\mu g\ g^{-1}$) as compared to all seeding rates except the lowest, and the summerfallow in this case had the lowest inorganic N compared to all other treatments at 7.2 $\mu g\ g^{-1}$. Differences at this site were slight and did not show a similar pattern to other sites.

In 2006, the changes in inorganic N between treatments were distinct (Table 3.11). Vanscoy had inorganic N concentrations of between 17 and 19 $\mu g\ g^{-1}$ for the summerfallow and green manure treatments at a soil depth of 0 to 15 cm. The seeding rate treatments were significantly lower, with concentrations ranging from 6.2 $\mu g\ g^{-1}$ at 10 plants m^{-2} to 8.3 $\mu g\ g^{-1}$ at 156 plants m^{-2}. At the 15- to 30-cm soil depth, levels of inorganic N were lower overall, but showed a similar trend as the 0- to 15-cm depth. That is, higher levels of inorganic N remained in the fallow and green manure treatments. The site at Vonda in 2006 exhibited a clearer trend than in 2005. The inorganic N concentrations at both the 0- to 15-cm and 15- to 30-cm depths were higher for the summerfallow and green manure treatments, but no significant differences occurred between seeding rates.

3.3.3 Effect of lentil seeding rate

3.3.3.1 Emergence

As in the field pea experiment, emergence rates for lentil were lower than expected. Emergence rates varied from 67% at the lowest seeding rate to 49% at the highest seeding rate, although emergence did not consistently decrease as seeding rate increased (Table 3.12).

Table 3.12 Emergence of organic lentil combined for sites in central Saskatchewan in 2005-06.

Seeding rate	Emergence	
(viable seeds m^{-2})	(plants m^{-2})	(%)
15	10	67*ab*[†]
38	20	53*ab*
94	62	66*a*
235	129	55*ab*
375	184	49b

[†]Means followed by the same letter within columns are not significant at $P \leq 0.05$ according to the least squares means test.

3.3.3.2 Crop and weed biomass

Crop biomass increased asymptotically as seeding rates increased (Fig. 3.3) from 314 to 3998 kg ha^{-1} between 15 and 375 seeds m^{-2}. One-half of the predicted maximum biomass accumulation occurred at 151 seeds m^{-2} (Table 3.13).

Weed biomass decreased from 3155 kg ha^{-1} to 1298 kg ha^{-1} as lentil seeding rate increased (Fig. 3.3). One-half of the weed biomass was suppressed at 228 seeds m^{-2} (Table 3.13) indicating that weed biomass was reduced at a slower rate than the rate of increase for crop biomass.

When crop and weed biomass were determined based on actual plant density, the D_{50} values were lower (Table 3.13). The crop density where half of the maximum crop biomass was reached was 114 plants m^{-2}, while the density where half of the weed biomass was reduced was 121 plants m^{-2}.

Broadleaved weeds dominated the weed population with the mean proportion of broadleaf weed biomass for all seeding rates ranging from 64 to 67% (Table 3.14). There were no significant differences for proportion of broadleaf weed biomass between treatments. Species of broadleaved and grassy weeds in the lentil trial were the same as those growing in the field pea trial (Section 3.3.2.2).

There were no significant differences for weed number between seeding rates (Table 3.14). There was a slight decrease in weed number, however, at high seeding rates.

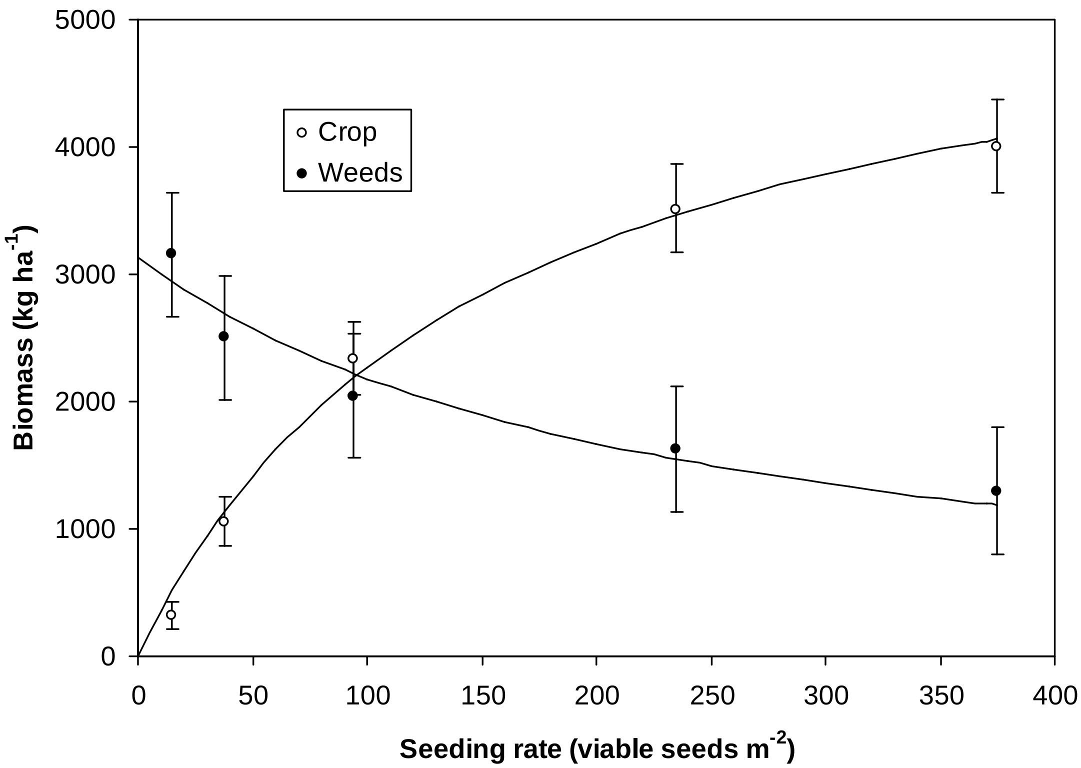

Fig. 3.3 Organically grown lentil crop and weed biomass at physiological maturity. Data represent four sites in central Saskatchewan combined for 2005 and 2006. Bars indicate one standard error of the mean.

Table 3.13 Parameter estimates (±S.E.) for organic lentil crop and weed biomass non-linear regressions based on Equations 3.3 and 3.4, respectively. Data combined for sites in central Saskatchewan in 2005 and 2006.

	Parameter estimates		
Variable	Y_{max} †	D_{50} ‡	R^2
Crop biomass	5697 (448.0) §	151 (28.5)	0.99
Weed biomass	3134 (207.5)	228 (56.6)	0.92
Grain yield	1690 (67.9)	124 (12.9)	0.99

† Y_{max} is the maximum yield

‡ D^{50} is the density at which one-half of Y_{max} is achieved

§ ± standard error in parentheses

Table 3.14 Proportion of broadleaved weeds in organically grown lentil combined between sites in central Saskatchewan in 2005 and 2006.

Seeding rate	Weed number	Proportion of broadleaved weeds
(viable seeds m^{-2})	(weeds m^{-2})	(%)
15	215	65
38	202	67
94	227	64
235	197	66
375	191	66
Diff. of LS means†	NS‡	NS

†Differences between least squares means
‡Not significant at $P \leq 0.05$

3.3.3.3 Grain yield

Lentil seed yield also increased with increasing seeding rate (Fig. 3.4) from 200 to 1291 kg ha^{-1} between 15 and 375 seeds m^{-2}. One-half of the predicted maximum grain yield was reached at 124 plants m^{-2} or 25 seeds m^{-2} less than half of the maximum crop biomass accumulation (Table 3.13). The disparity between when half of the maximum yield and crop biomass amounts were reached was reflected by reduced harvest index at the highest seeding rate (Table 3.15).

When actual crop density was plotted with grain yield, the D_{50} value was lower than when seeding rate was used at 88 seeds m^{-2}. The difference between the crop density where half of the maximum grain yield and crop biomass were reached was 26 seeds m^{-2}, which was similar to the difference when seeding rate was used (Table 3.13).

A comparison of mechanical and hand-harvested seed samples showed that hand-harvested samples consistently yielded greater than the mechanically-harvested samples (Table 3.15).

3.3.3.4 Yield and seed quality components

Harvest index values provided evidence that less grain was produced per kg of aerial biomass than at lower plant densities. Harvest index did not change between seeding rates except a decrease at the highest seeding rate from 0.43 to 0.40 (Table 3.15), indicating that more vegetative biomass was produced at the highest crop density than any other.

Water use efficiency increased as seeding rate increased (Table 3.15). This was due to the lack of difference in soil water storage at harvest between seeding rates.

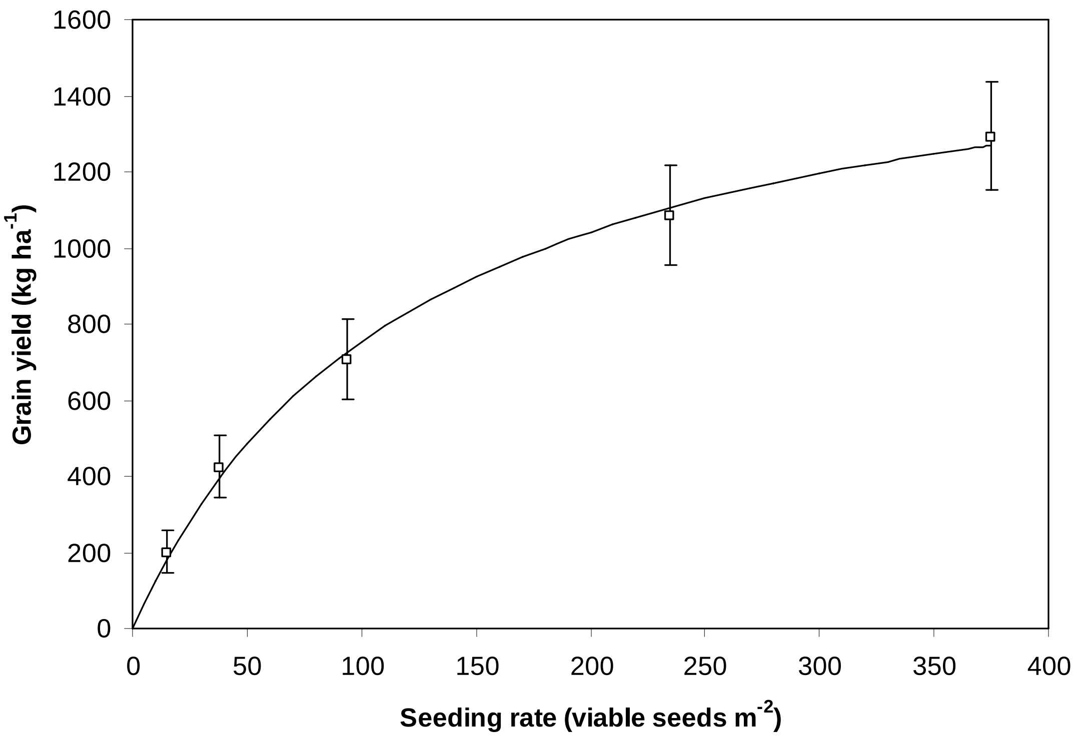

Fig. 3.4 Impact of seeding rate on grain yield of organically grown lentil. Data represent combined sites analyses for four sites and two years (Vonda and Delisle in 2005, and Vonda and Vanscoy in 2006). Bars indicate one standard error of the mean.

Table 3.15 Yield components for organically-grown lentil combined between sites in central Saskatchewan in 2005 and 2006.

Seeding rate (viable seeds m^{-2})	Harvest index (seed:seed+straw)	WUE (kg ha^{-1} mm^{-1})	100 Seed wt (g 100 $seeds^{-1}$)	Hand-harvested yield (kg ha^{-1})	Mechanical yield (kg ha^{-1})
15	0.43*ab*	0.35*c*	6.7*b*[†]	200	105
38	0.42*a*	1.45*bc*	6.8*ab*	423	371
94	0.43*a*	2.31*ab*	6.9*a*	706	606
235	0.43*a*	2.96*ab*	6.8*ab*	1083	815
375	0.40*b*	3.64*a*	6.9*ab*	1291	1041

[†] Means followed by the same letter within columns are not significantly different at $P \leq 0.05$ according to pairwise comparisons of least squares means

Because water use was very similar between treatments, WUE increased as yield increased, as it is a measure of the amount of grain produced per unit of available moisture during the growing season.

Seed quality changed little between seeding rates. Seed weight was significantly lower at the lowest seeding rate than the rest, but the difference was minimal (0.1 g 100 $seeds^{-1}$) (Table 3.15). Seed grade by visual inspection resulted in a rating of 'Grade 2' according to the CGC standards for all samples in 2005 and 2006.

Incidence of disease in lentil was not problematic at the highest crop density (Stephanie Boechler, personal communication). The most common disease-causing agent was *Alternaria sp*. with 5% of lentil seeds tested infected (Table 3.16).

Seed P concentration did not change significantly between treatments, but did show an increasing trend with increasing seeding rate (Table 3.17). Straw P also did not change significantly between treatments, but was higher at the highest seeding rate than at any other density (Table 3.17). As a result, the ratio of seed P:straw P was lowest at the highest seeding rate, but varied little between the other treatments (Table 3.17). Because seed and straw P concentrations did not change, seed and straw P uptake showed similar increasing patterns with increased seeding rate as the yield data did (Table 3.17; Table 3.15).

Table 3.16 Percent incidence of various seed-borne disease-causing agents at the highest seeding rate for lentil (375 plants m^{-2}) combined for all sites in 2005 and 2006.

Crop	*Alternaria*	*Fusarium*	*Ascochyta*	*Mycosphaerella*	*Stemphylium*	*Botrytis*
Lentil	5.0	0.2	0.1	n/a	0.1	n/a

Table 3.17 Seed and straw P uptake and concentration after harvest for organically grown lentil combined between sites in central Saskatchewan for 2005 and 2006

Seeding rate (viable seeds m^{-2})	Seed P uptake (kg ha^{-1})	Straw P uptake (kg ha^{-1})	Seed P conc. (mg kg^{-1})	Straw P conc. (mg kg^{-1})	Ratio (seed P:straw P)
15	0.6*d*	0.05*d*	2781	430	6.5
38	1.1*c*	0.3*cd*	2704	409	6.6
94	1.9*b*	0.6*c*	2738	359	7.6
235	3.2*ab*	1.1*bc*	2928	436	6.7
375	3.8*a*	1.7*ab*	2917	597	4.9
Diff. of LS means†			NS‡	NS	NS

†Differences between least squares means

‡Not significantly different within columns at $P \leq 0.05$

3.3.3.5 Soil nutrients at harvest

Soil nutrient data were separated by year and site because original levels at the outset of the field trials varied at each site. The Vonda and Vanscoy sites showed significant differences for available soil P. Vonda in 2005 showed the highest available soil P in the summerfallow and 38 plants m^{-2} seeding rate, and the lowest soil P at 94 and 375 plants m^{-2} (Table 3.18). At Vanscoy, the lowest rate of green manure was lower in soil P than the higher green manure seeding rate, as well as the lowest two grain seeding rates (15 and 38 plants m^{-2}) and the second-highest seeding rate (235 plants m^{-2}). Although some of the differences within sites were significant at $P \leq 0.05$, the amount of variability surrounding the values was high and differences showed no trend in terms of seeding rate or management practice either within sites or between sites. When compared with available P in spring (Table 3.1), all sites showed a reduction in soil P at harvest.

Total percent N in soil did not differ consistently between treatments for each site. The one site where significant differences were detected was in Vanscoy in 2006, where the lowest seeding rate (15 plants m^{-2}) had the highest % N and was significantly higher than the lowest rate of green manure and the middle seeding rate of 62 plants m^{-2}, although this value was not significantly different than most of the other seeding rates (Table 3.18).

Inorganic N varied more than total percent N (Table 3.18). The general trend, as with field pea, was for higher concentrations for the summerfallow and green manure treatments and lower concentrations where lentil were grown as grain legumes at both the 0- to 15-cm and 15- to 30-cm soil depths.

In 2005, Delisle exhibited this trend, as the inorganic N concentration reached 21 $\mu g\ g^{-1}$ for the green manure treatment and was only 9.5 $\mu g\ g^{-1}$ for most seeding rates at the 0- to 15-cm soil depth. Inorganic N increased slightly at the highest seeding rate to 10.5 $\mu g\ g^{-1}$. At the Vonda location, however, there were no significant differences between treatments.

Table 3.18 Soil nutrient availability after harvest for organic lentil combined between sites in central Saskatchewan for 2005 and 2006.

Seeding rate	Available P	Total N	Inorganic N	
(viable seeds m^{-2})	($\mu g\ g^{-1}$)	(%)	($\mu g\ g^{-1}$)	
Delisle 2005	0-15cm	0-30cm	0-15cm	15-30cm
Summerfallow	2.4	0.19	15.8*ab*†	16.3*ab*
Green manure	2.8	0.20	21.1*a*	22.0*a*
15	2.5	0.18	9.4*c*	8.2*c*
38	2.7	0.19	9.5*c*	8.8*c*
94	2.4	0.21	9.5*c*	8.1*c*
235	2.5	0.19	9.7*c*	8.9*c*
375	2.6	0.22	10.5*bc*	11.1*bc*
Diff. of LS means‡	NS§	NS		
Vonda 2005				
Summerfallow	1.8*a*	0.16	9.2	7.4
Green manure	1.6*ab*	0.15	9.7	8.2
15	1.6*ab*	0.17	9.4	8.1
38	1.8*a*	0.16	11.0	8.3
94	1.4*b*	0.17	10.0	8.0
235	1.6*ab*	0.16	10.2	8.0
375	1.4*b*	0.16	10.9	9.2
Diff. of LS means		NS	NS	NS
Vanscoy 2006				
Summerfallow	3.5*ab*	0.19*ab*	15.0*a*	8.4*a*
Green manure	3.2*b*	0.18*b*	11.3*b*	6.4*b*
Green manure (2x)	3.6*a*	0.19*ab*	15.2*a*	6.4*b*
15	3.7*a*	0.22*a*	4.2*c*	3.4*c*
38	3.6*a*	0.20*ab*	4.1*c*	3.3*c*
94	3.5*ab*	0.19*b*	3.8*c*	3.0*c*
235	3.6*a*	0.20*ab*	4.4*c*	3.4*c*
375	3.4*ab*	0.20*ab*	4.2*c*	3.2*c*
Vonda 2006				
Summerfallow	1.8	0.13	8.2*ab*	6.4*b*
Green manure	1.6	0.14	8.7*ab*	8.3*b*
Green manure (2x)	1.6	0.13	10.0*a*	11.7*a*
15	1.4	0.12	3.5*b*	4.5*c*
38	1.2	0.13	3.4*b*	4.7*c*
94	1.6	0.14	4.2a*b*	5.1*c*
235	1.3	0.13	3.5*b*	4.7*c*
375	1.4	0.14	3.6*b*	4.7*c*
Diff. of LS means	NS	NS		

†Means followed by the same letter within columns are not significantly different at $P \leq 0.05$

‡Differences between least squares means

§ Not significantly different within columns at $P \leq 0.05$

In 2006, the results from the two sites were similar (Table 3.18). As with the majority of sites for both crops, inorganic N concentrations were the highest for the summerfallow and green manure crops. At both sites, the 2x green manure seeding rate had higher concentrations of inorganic N than the 1x seeding rate, although the difference was only significant at Vanscoy. In contrast to the field pea trials, however, the highest seeding rates did not have higher soil inorganic N than the lower seeding rates (Table 3.10; Table 3.18).

3.4 Discussion

Normal to high levels of precipitation may increase crop and weed biomass production (Wall et al., 1991; Ball et al., 1997; Jettner et al., 1999). In an Australian study, Jettner et al. (1999) found that at most study sites chickpea yield was higher in a year with above-average precipitation than a year with below-average precipitation when weeds were controlled with herbicides. Ball et al. (1997) reported that weed seedling densities were higher at one of two locations when precipitation was high as compared to the 30 y mean in an Australian lentil seeding rate study. Wall et al. (1991) found that wild mustard abundance increased as growing season precipitation increased, and that field pea yield was reduced to a greater extent in years with higher levels of precipitation than average. In our field study, weeds may have been more abundant and competitive than in an average year, and crop yield may have been reduced to a greater extent, as weeds were not controlled with herbicides in this study.

The trend for increasing crop yield and biomass with increasing seeding rate has been demonstrated in a number of studies. The increase in biomass and yield up to the highest crop density is supported by McDonald et al. (2007), who found that pea yield increased to the highest treatment density of 200 plants m^{-2}. Similarly, Lawson (1982) found that pea yields increased with increasing plant density up to 140 plants m^{-2} in one experiment, and up to 195 plants m^{-2} in another. Another study found that increased seeding rates increased pea biomass production and yield in stress conditions (Boerboom and Young, 1995). In lentil, Ball et al. (1997) found that seed yield increased at most study sites when seeding rate was doubled from 22 to 44 kg ha^{-1} (63 to 126 plants m^{-2}). There have been studies, however, that dispute these findings.

Johnston et al. (2002) discovered no increase in seed yield associated with increased seeding rate between 50 and 150 plants m^{-2} for semi-leafless pea. These rates are comparable to the rates used in our study, but our results refute those of Johnston et al. (2002), as yield increases occurred between all seeding rates, from 10 to 250 plants m^{-2}. Johnston et al. (2002) also found, however, that where weed management was not optimal seeding rates higher than 50 seeds m^{-2} reduced weed biomass and increased seed yield.

The Michaelis-Menten equation described the biomass and crop yield means well (R^2=0.92 to 0.99). Typically, the Michaelis-Menten equation is used to describe enzyme kinetics, whereas in this study it was used in a novel manner to describe the effects of increasing seeding rate on crop biomass and yield in a weedy setting, and modified to describe weed biomass reduction with increasing seeding rate. This equation is algebraically equivalent to Watkinson's yield density equation (Firbank and Watkinson, 1990), but the parameters are more meaningful. Previously, the Michaelis-Menten equation was adapted by Jolliffe et al. (1984) to describe crop yield for a single species grown without interspecific competition. Other workers have used a variety of equations to describe crop yield trends with increasing seeding rate, including asymptotic (Gooding et al., 2002), linear (McDonald et al., 2007), and quadratic (Lawson, 1982) curves.

Weed biomass was reduced by 68% in field pea and 59% in lentil between the lowest and highest seeding rates (Fig. 3.1, Fig. 3.3). Weed biomass was reduced by 24% and 26% above the rate recommended for conventional production of field pea and lentil, respectively. These results are consistent with the findings of many studies. Grevsen (2003) found that weed biomass decreased by 30 to 50% when seeding rate of green pea was increased from 90 to 150 plants m^{-2}. Similarly, Boerboom and Young (1995) reported a reduction in weed biomass when crop density was increased by more than 50% above the recommended rate of 88 plants m^{-2} for pea and 130 plants m^{-2} for lentil, although the weed density did not decrease. In lentil, an increase in crop yield decreased canola yields where canola was considered a weedy species (McDonald et al., 2007). Ball et al. (1997) found that weed dry weight was reduced by 20 to 60% when the seeding rate of lentil doubled from 63 to 126 plants m^{-2}, depending on the seed placement. The 20% reduction in weed dry weight resulted from seeding the lentil in one direction, while the 60% reduction occurred when the crop was seeded at half the rate in one direction, then again at half the rate perpendicular to the first seeding pass. Weed biomass also decreased as lentil density increased to 359 plants m^{-2} in a study by Paolini et al. (2003). Paolini et al. (2003) determined that lentil was less competitive than weeds at densities less than 177 plants m^{-2}, equally as competitive at 177 plants m^{-2}, and at crop densities above, lentil were more competitive than weeds. The proportion of weed biomass reduced by tillage and plant density was 48%, 64% and >84%, respectively. Environmental conditions may have played a role in the competitiveness of the weeds and crop. Wall et al. (1991) found that wild mustard interference was highest with high levels of precipitation. The temperature and precipitation were higher than normal for most of the growing season in both years and may have increased the competitiveness of weed species such as wild mustard which was prevalent at Vonda in both years.

The total number of weeds did not change significantly for field pea or lentil. This indicates that the increased competitiveness of the crop at high seeding rates resulted in less biomass produced per weed rather than a weed number reduction. Ball et al. (1997) reported weed seedling reductions of 50%, 17% when doubling the lentil seeding rate from 63 to 126 plants m^{-2} at one site, while another site showed no difference in the number of weeds between seeding rates. Similarly, Wall and Townley-Smith (1996) found that weed density was negatively correlated to field pea seeding rate in one of three years, while weed dry matter was correlated to seeding rate in two of three years. Weeds may have produced less seed per plant due to their smaller size.

Broadleaved weeds were more common than grassy weeds in both the field pea and lentil trials. The most common weeds found in the sites studied are consistent with a weed survey performed in Saskatchewan on 73 organic farms where green foxtail, wild mustard, lambsquarters and wild buckwheat were the most common weeds found (Buhler, 2005). In a study by Hock et al. (2006), broadleaved weeds were more competitive than grassy weeds in a soybean crop; however, the density of grassy weeds was low. In Nebraska, Hock et al. (2006) developed competitive indices (CI) for each weed species grown with the crop based on weed dry matter, weed volume and crop yield loss. Broadleaved weeds had higher CI values than grassy weeds (i.e., broadleaved weeds were more competitive) when grown with soybean.

The proportion of broadleaved weeds did not change significantly between seeding rates, indicating that both broadleaved and grassy weeds were reduced by similar proportions as seeding rates increased. Interestingly, the proportion of broadleaved weeds was approximately 15% higher for field pea than lentil, even though both crops were planted at each site. Reasons for this discrepancy between crops are difficult to elucidate; the proportion of broadleaved weeds may have been affected by varying environmental conditions created by the two crops. Field pea is more competitive than lentil (Mishra et al., 2006) and may have reduced grassy weed seedling growth better with greater surface area coverage by leaves early in the season.

Harvest index was reduced at high crop densities for both field pea and lentil. Proportionally more biomass than seed was produced at high plant densities. Other studies have reported similar results. Siddique et al. (1998) found that harvest index was reduced at high lentil densities up to 274 plants m^{-2} in Australia. However, Paolini et al. (2003) reported an increase in harvest index with increasing lentil density between 125 and 358 plants m^{-2}. A study of vining pea reported a lower number of branches, pods and seeds per pod with high plant densities (Lawson, 1982).

The overestimation of seed yield associated with the hand-harvested samples may have occurred due to the greater care taken with hand-harvesting rather than those harvested by plot combine and some unintentional over-sampling.

There was no reduction in seed quality as seeding rate increased as assessed by seed weight and visual seed grading. Similar results were obtained by Lawson (1982), where there was no reduction in grain weight in vining pea as seeding rate increased from 11 to 194 plants m^{-2}. Johnston et al. (2002) found no reduction in semi-leafless pea weight at one study site between 50 and 150 plants m^{-2}, but did report reduced seed weight at high crop densities at another site.

Disease incidence was not a concern for field pea or lentil at the highest seeding rates. Other researchers have found, however, that high plant densities increased the incidence of disease (Hwang et al., 2006; Chang et al., 2007). Hwang et al. (2006) found that mycosphaerella blight severity increased with increasing field pea density between 30 and 150 plants m^{-2}. Similarly, Chang et al. (2007) found that ascochyta blight severity was positively correlated to chickpea density in an Alberta study; however, the researchers also noted that disease severity was affected more by crop cultivar than by plant density. The above studies managed weeds with herbicides, whereas our study included naturally-occurring weeds. The presence of a variety of weeds in our study may have lessened disease severity as most disease-causing agents do not affect all species found in the field, but rather a single species or genus (Agrios, 1997). The cultivars used in our study also had relatively good disease resistance ratings as compared to other cultivars with good resistance to ascochyta blight for lentil and fair resistance to mycosphaerella blight for field pea (Saskatchewan Seed Growers Association, 2006).

The ratio of seed P:straw P was higher for lentil than has been previously reported. The ratios in this study ranged from approximately 5 to 7.5, whereas Selles et al. (1995) found that the average ratio for lentil was 5. In the study by Selles et al. (1995), however, all treatments were fertilized.

Straw from organic lentil may return less P to the soil for subsequently grown crops than conventional lentil. In a conventional lentil study, the mean amount of P in lentil straw was 0.8 g kg^{-1} (Selles et al., 1995), whereas in our study, straw P averaged 0.4 to 0.5 g kg^{-1}. Selles et al. (1995) also found that withholding P fertilizer decreased P removed by the seed and straw in lentil. This may be an important observation, as the loss of P in arable organic farms over time has been documented and is a concern for organic farmers (Watson et al., 2002a). The soil at our sites had not been amended with manure for a minimum of 3 y prior to the initiation of the study. A mean loss of 6 kg P ha^{-1} y^{-1} was measured for organic farms that did not incorporate animal manure as a means of maintaining soil fertility (Watson et al., 2002b). Gosling and Shepherd (2005) stated that where animal manure was not applied soil P reserves were likely to become depleted in organic systems. Oehl et al. (2002) confirmed that soil P was depleted over time in organic production systems, where non-fertilized soil produced a negative P budget over 21 years with a mean loss of 21 kg P ha^{-1} for each of three 7 y rotations. Seed P concentration was also lower for organic lentil when compared to a conventional study. Seed P concentrations in our study ranged from approximately 2.8 to 2.9 g kg^{-1}, while the conventional lentil seed P concentrations ranged from 3.62 to 4.3 g kg^{-1} (Selles et al., 1995; Gahoonia et al., 2005). Total P uptake in the seed, however, was similar at the highest seeding rates (235 and 375 plants m^{-2}) to the conventional seed P uptake of 3.65 kg ha^{-1} (Selles et al., 1995). Our seeding rates where seed P uptake was similar to conventional lentil was much higher than the recommended rate for conventional production of the crop of 130 plants m^{-2} (Saskatchewan Pulse Growers, 2000), and may be due to the increased density and biomass production.

Phosphorus uptake by field pea was much lower in our organic trial as compared to a conventional study where no N fertilizer was added (Deibert and Utter, 2004). Seed P uptake in the conventional experiment averaged 8.6 kg ha^{-1} at harvest, while our results were lower at 3.8 kg ha^{-1} (Table 3.8). Although little information was found regarding field pea straw and P concentration or uptake, it is likely that straw P uptake would also be lower for our study when compared to conventional P uptake levels.

Soil P differed significantly between seeding rates, but the high degree of variability associated with the values indicates that the differences were likely due to spatial variability within each site rather than treatment effects (Table 3.11, Table 3.18). These results are not unique; Gosling and Shepherd (2005) found that there was no difference in extractable P concentration between low and high fertility phases of organic farms. A number of parameters can influence P availability in the soil, such as environmental conditions. Soil P availability is highly related to microbial activity and microorganisms are sensitive to environmental conditions such as soil moisture, aeration, temperature and pH (Havlin et al., 1999). All sites showed a decrease in available soil P between spring and harvest. This may be due to the presence of a higher proportion of weeds in low seeding rate treatments that equalized P uptake between treatments. Gosling and Shepherd (2005) also reported a decrease in P levels over time in organic systems where P inputs did not include manure.

Total percent soil N did not change consistently with seeding rate; however, soil inorganic N did change (Table 3.11, Table 3.18). Treatments where no grain was harvested (i.e., summerfallow and green manure) generally had the highest levels of inorganic N. This was expected, as no nutrients were removed from the system and weed and crop biomass was incorporated into the soil prior to harvest when the soil samples were taken. Other studies have reported both gains and losses in soil N after growing green manure crops or grain legumes. For example, pea as a green manure crop provided a positive N balance in a Saskatchewan study, returning as much as 14 kg N ha^{-1} (Stevenson and van Kessel, 1996). Schmidtke et al. (2004), however, found that lentil provided a slightly negative N balance when grown as a grain crop. Field pea grown as a grain legume also provided an increase in soil N in one study (Maidl et al., 1996).

There was no treatment that was consistently higher in soil inorganic N than the other (Table 3.10, Table 3.16). Where two rates of green manure crops were grown in 2006, the 2x rate generally left higher levels of inorganic N than the 1x rate for both crops. Similarly, high seeding rates of field pea had slightly higher soil inorganic N levels than lower seeding rates at harvest. This was likely caused by: i) a reduction in the amount of weed biomass, and ii) an increase in the crop density that is fixing atmospheric N_2. At higher seeding rates less N uptake by weeds occurred, as there was less weed biomass. More of the total biomass produced per unit area was field pea at high seeding rates, and field pea fixed atmospheric N_2 as a proportion of the total N requirement of the crop. Moreover, HI decreased indicating that more straw was returned to the soil relative to export of N in the seed at higher seeding rates, allowing for a greater level of nutrient recycling at high seeding rates. For these reasons, less N uptake may have occurred at high seeding rates than at lower seeding rates where weed biomass was higher and crop biomass lower. This trend was less evident for lentil; however, weed biomass was higher in lentil even at the highest seeding rate and may have contributed to higher N uptake from the soil at the highest crop density. Caution must be taken when interpreting these results, as the soil samples were taken at harvest and no residues were incorporated for the grain legume treatments. Soil inorganic N levels may, in fact, be higher for the grain legume treatments (and summerfallow and green manure treatments) in spring where residues may be further decomposed.

3.5 Conclusions

Increasing seeding rates of field pea or lentil will increase crop biomass production and yield, although the proportion of grain to straw produced decreases slightly as seeding rate increases. Weeds in organic production systems can be suppressed by increasing seeding rates. When comparing weed biomass between the highest rates used and the rates recommended for conventional production of these crops, weed biomass decreased by 24% between 88 and 250 plants m^{-2} in pea and by 26% between 130 and 375 plants m^{-2} in lentil. Seed quality, plant P uptake and soil water storage were not significantly affected by seeding rate and are not a constraint to increasing seeding rates. At harvest, inorganic soil N was lower in the grain legume treatments than the summerfallow and green manure treatments. When inorganic N was examined within the grain legume treatments, however, the highest concentrations occurred in the higher seeding rates. This is encouraging for organic producers who wish to increase seeding rates to manage weeds, but are concerned about soil N losses. Organic farmers will benefit from increasing seeding rates beyond the recommended rate for conventional production to manage weeds.

Further research investigating the proportion of N uptake occurring through N_2 fixation for each crop at varying seeding rates would be helpful to elucidate why soil inorganic N levels vary with seeding rate. A soil test in spring following the harvest of field pea or lentil would also be a better indicator of available soil N for plant growth, as crop and weed residues may be further decomposed and might provide more inorganic N than indicated by the soil test at harvest.

4. ARBUSCULAR MYCORRHIZAL FUNGI COLONIZATION AND PHOSPHORUS NUTRITION IN ORGANIC FIELD PEA AND LENTIL

4.1 Introduction

Phosphorus is an important macronutrient in the early stages of plant growth for energy storage and transfer, as a component of many structural compounds and for increased root growth (Havlin et al., 1999). On many organic arable farms where animal manure is not applied, P is the limiting nutrient to crop production (Malhi et al., 2002; Knight and Shirtliffe, 2003). Consequently, methods to increase crop uptake of P are important for organic systems. Phosphorus is a relatively soil-immobile nutrient and is accessed by plant roots through contact (Havlin et al. 1999). Arbuscular mycorrhizal fungi (AMF) colonize most crop plant roots and increase P uptake by increasing the volume of soil explored with hyphae (Mosse et al., 1981; Francis and Read, 1997). Increased acquisition of P by the crop can increase its vigour and yield (Dodd, 2000; Chen et al., 2005).

The objectives of this study were: i) to determine the impact of seeding rate on AMF colonization and ii) to determine if AMF colonization rate and levels affect P concentration and uptake by field pea and lentil in an organic system.

4.2 Materials and Methods

4.2.1 Field study

4.2.1.1 Site description and experimental design

Two locations were chosen on commercial organic farms in 2005 (Vonda and Delisle, Saskatchewan) and 2006 (Vonda and Vanscoy, Saskatchewan). Climatic data were recorded during the growing season by weather stations set up in close proximity to the research plots. Soil samples for nutrient status and moisture content were taken prior to seeding to 120 cm and at harvest in each plot to 30 cm as previously described

(Section 3.2.1). Soil samples taken prior to seeding were analyzed by ALS Laboratory Group (Table 3.1). Samples taken after harvest were analyzed for available phosphate-P by ALS as previously described (Section 3.2.1).

In each location, field pea (*Pisum sativum* cv CDC Mozart) and lentil (*Lens culinaris* cv CDC Sovereign) were seeded at five rates: 10, 25, 62, 156 and 250 plants m^{-2} and 15, 38, 94, 235 and 375 plants m^{-2} respectively. Seeding rates were adjusted to account for the results of germination tests as previously described (Section 3.2.1). Each site was seeded in a randomized complete block design with four replicates and a single plot size of 2 x 6 m in 2005 and 4x 6 m in 2006. The larger plot size in 2006 allowed for an undisturbed 2 x 6 m strip for mechanical harvest. Plots were managed as previously described in Section 3.2.1. Aboveground weed and crop biomass was collected (two 0.25 m^2 quadrats per plot), dried and weighed to determine the weed densities of hosts and non-hosts of AMF with the various seeding rates. Non-host weeds [*Sinapis arvensis* (wild mustard), *Chenopodium album* (lambsquarters) and *Capsella bursa-pastoris* (Shepherd's purse)] (Mosse et al., 1981; Feldmann and Boyle, 1999) were separated from the rest of the weed biomass at sampling.

A sample of the crop from four 1 m long rows (equivalent to an area of 81 cm^2 per plot) was taken at harvest. Methods for drying, threshing, and analyzing the seed and straw are described in detail in Section 3.2.

4.2.1.2 Root sampling and analysis

Prior to ploughdown of the green manure, five representative bulk root samples from each treatment were collected by excavating the soil from around the crop rows to a depth of 15 cm (Germida and Walley, 1996). Samples were stored at 4˚C until soil was washed from the roots by wrapping plastic mesh around the sample and gently massaging underwater until only roots and debris were left within the mesh enclosure. The roots were separated from the debris by immersing in water and removing the roots using tweezers. Roots were sliced into approximately 1 cm sections and stored at 4˚C in a 50% ethanol solution (Koske and Gemma, 1989) until further analysis was performed. Percent colonization of roots by AMF was determined using the ink and vinegar staining technique described by Vierheilig et al. (1998). Briefly, root samples were placed into cassettes and cleared by immersion in a boiling 10% KOH solution for 12 min. Samples were then rinsed in tap water and placed in a boiling solution of 5% black India ink and vinegar for 3 min to stain the fungal structures. Samples were rinsed again with tap water and placed into a destaining solution of tap water and a few drops of vinegar for 7 d at room temperature (Vierheilig et al., 1998). Percent colonization was assessed by the gridline intersect method (Giovannetti and Mosse, 1980). Root samples with a fresh weight of approximately 1 g were placed in a Petri dish with gridlines 0.5 cm apart. Roots were laid out so as to not overlap, and were assessed with a dissecting microscope at 50X magnification for any AMF structures, including hyphae and vesicles. One hundred observations were recorded for each sample, and four replicates were sampled for the low, middle and high seeding rates at each site.

4.2.2 Growth chamber experiment

4.2.2.1 Experimental design

The soil used for this experiment was collected from the Ap horizon (0 to 15 cm) of an organically-managed field near Vonda that had not had pea grown on it for the previous 3 y to reduce potential incidence of disease. The soil was air dried for two weeks, then mixed with silicate sand at a ratio of 1:1 (vol.). A bulk soil sample was collected from the field and the soil characteristics were assessed by ALS Laboratory Group (Table 4.1).

Three densities of pea corresponding to low (10 plants m^{-2}), medium (62 plants m^{-2}) and high (250 plants m^{-2}) seeding rate targets used in the field were planted in pots with a surface area of 615 cm^2 and 20 cm depth. Four replicates and five sampling times were used for a total of 60 pots. The low seeding rate treatment contained one plant pot^{-1}, the mid-range seeding rate contained four plants pot^{-1}, and the high seeding rate contained 16 plants pot^{-1}. Two seeds were planted for the low rate, six seeds for the mid-rate, and 20 seeds for the high rate, and then thinned at emergence to achieve the target plant densities. Seeds were pre-germinated in the dark on moist paper towel for 72 h, and then planted to a depth of 2 cm (Manitoba Agriculture, 2004).

Table 4.1 Characteristics of soil collected from the top 15cm of the soil profile mixed with silicate sand (1:1) (vol.) used in the growth chamber

Site	Vonda
Location	52°18'08"N 106°06'00"W
Soil zone	Black
Soil texture	Sandy loam
pH	8.3
E.C. (mS cm^{-1})	0.2
Soil test $N0_3$-N (mg kg^{-1})	30.8
Soil test P (mg kg^{-1})	52.8

Seeds were inoculated with *Rhizobium leguminosarum* (strain P108) from Philom Bios (Saskatoon, SK.). The inoculant was diluted in a phosphate-buffered saline solution to a concentration of 4×10^8 cfu mL^{-1}. One mL of solution was pipetted onto each seed before covering with soil.

Pots were placed in a growth chamber and covered with a transparent polypropylene sheet after seeding to conserve soil moisture. The sheet was removed once all plants had emerged and were thinned, six days after the seeds were planted. After thinning the plants to the target density, plastic beads were placed on the soil surface to reduce evaporation. Pots were watered to 65% of field capacity by weight every day.

Field capacity was determined by saturating four soil samples in open-ended cylinders. The samples were allowed to drain by gravity for 48 h. A 20 g subsample was taken from each sample and oven-dried for 72 h at 105˚C. Gravimetric soil moisture was determined from the subsamples and averaging the results from the four samples. The amount of water in 20 g of soil was multiplied by the amount of soil in one pot, and then 65% of field capacity for the weight of one pot was determined.

The growth chamber provided a 16 hour photoperiod and day/night temperatures of 21/18°C. Light intensity in the growth chamber varied by up to 50% between locations, from 262 to 525 µmoles m^2 s^{-1}. The pots were re-randomized every five days to reduce the variability associated with differences in light intensity. Weed seedlings that emerged were removed daily.

4.2.2.2 Biomass sampling and analysis

Harvests occurred at 10 d intervals, beginning 13 DAP or 10 d after emergence (DAE). Four replicates of each seeding rate were selected at random for each harvest. The aboveground plant tissue was removed, placed in a paper bag and dried for 72 h at 60ºC. Plant biomass was weighed and ground, and P concentration was determined by acid digestion (Thomas et al., 1967) and analyzed using a Technicon AutoAnalyzer II (Technicon Industrial Systems, Tarrytown, N.J.) as previously described (Section 3.2.1). Soil was washed from the roots with pressurized water. Roots were collected, stained and assessed as previously described (Section 4.2.1).

4.2.3 Statistical analysis

Data were analyzed using the PROC MIXED procedure of SAS (SAS Institute Inc., 2004) with block and site-year as random effects for the field study. Sites and years were combined for each crop, as the site-year*treatment interaction was not significant at $P \leq 0.05$ (Table A.3). Percentage data were arcsine-transformed prior to analysis. Nutrient data were transformed as required to meet the assumption of homogeneity of variance (Table 4.2). Back-transformed data are presented. Treatment effects were considered significant at $P \leq 0.05$.

A logistic growth equation was fitted to the means for P concentration and uptake data using the PROC NLIN procedure of SAS (SAS Institute Inc., 2004). The logistic function has been used to describe theoretical P uptake by mycorrhizal plants (Janos, 2007) and actual P uptake by crops such as winter wheat (Barraclough, 1989). A four-parameter logistic equation was used in this case, as it provided the best fit to the data using Sigmaplot 10.0 (Systat software, Inc.) :

$$y = y_0 + a/[1 + (x/x_0)^b] \qquad [4.1]$$

where y_0 = the lower asymptote of P uptake, a = the upper asymptote of P uptake, x_0 = days after emergence where half of P uptake occurs, and b = the slope factor that describes how quickly P is increasing in the plant.

Table 4.2 Data transformations to satisfy the homogeneity of variance assumption for PROC MIXED.

	Growth chamber	Field study	
Variable	Field pea	Field pea	Lentil
AMF colonization	Arcsine	Arcsine	Arcsine
Plant biomass	Ln†	√‡	√
Seed P concentration		None	None
Straw P concentration		None	Ln
Seed P:Straw P		None	None
Seed P uptake		√	√
Straw P uptake		√	√
Biomass P concentration	None		
P uptake pot^{-1}	None		
P uptake $plant^{-1}$	Ln		

†Natural log transformation

‡Square root transformation

4.3 Results

4.3.1 Arbuscular mycorrhizal fungi colonization

4.3.1.1 Growth chamber experiment

A visual assessment of the roots at harvest indicated good nodulation of all treatments. There were no noticeable differences in degree of nodulation between treatments; however, nodules on roots in the highest density treatment were slightly smaller than in the other two treatments.

When roots from the growth chamber experiment were assessed for AMF colonization, a steady increase in percent colonization occurred between the first and third harvest (Fig. 4.1). After the third harvest 30 DAE, the lowest plant density reached a plateau at approximately 60% colonization whereas the higher two plant densities continued to experience increased AMF colonization, and by the fourth harvest (40 DAE) the colonization level between the lowest and highest seeding rate was significantly different at $P \leq 0.05$. At the final harvest 50 DAE, both the 4 and 16 plant pot^{-1} treatments showed significantly higher colonization rates than the lowest one-plant treatment at $P \leq 0.05$. The medium and high density growth chamber treatments reached an average colonization rate of over 80% at 50 DAE.

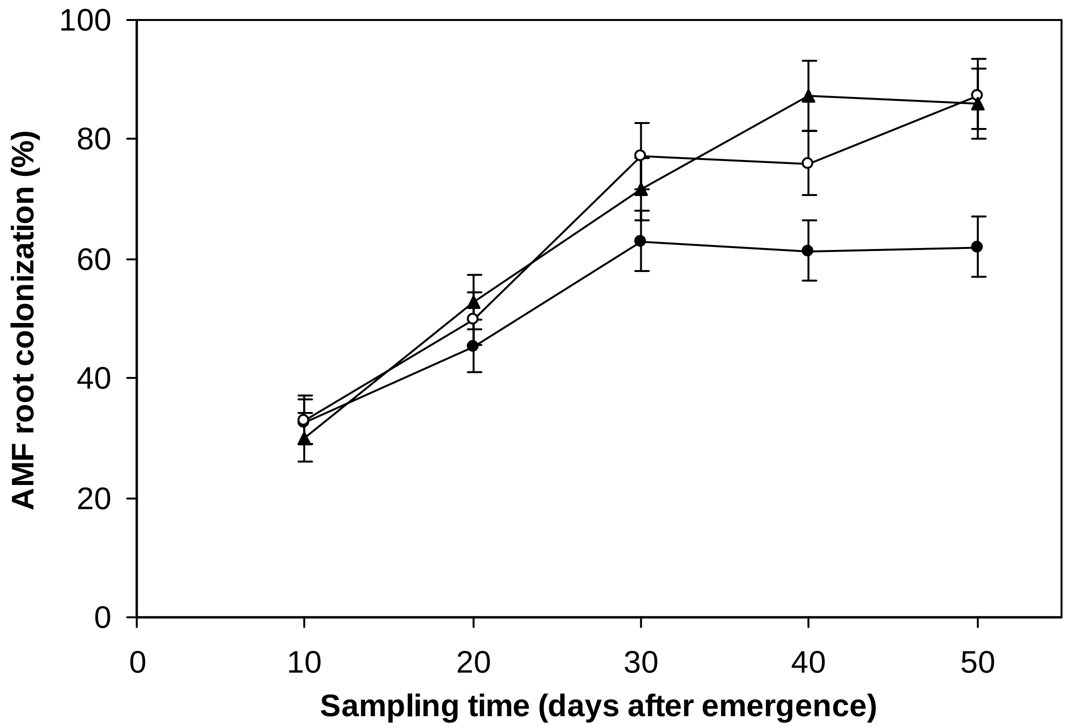

Fig. 4.1 Percent of field pea root colonized by AMF at five harvest dates in the growth chamber. Plant densities correspond to (●) low (10 plants m^{-2}), (○) medium (62 plants m^{-2}) and (▲) high (250 plants m^{-2}) target densities previously used in field trials. Bars indicate one standard error of the mean.

4.3.1.2 Field experiment

Field samples supported the findings of the growth chamber experiment in that relatively high levels of colonization were achieved (Fig. 4.2). Roots from the low, medium, and high seeding rates in the field were assessed for both crops. Field pea showed considerable variability within treatments, but no significant differences were detected between the seeding rates (Fig. 4.2). Conversely, lentil root colonization levels showed significant differences between the three seeding rates (15, 94 and 375 plants m^{-2}) and less variability within treatments (Fig. 4.3). The colonization levels of the three lentil seeding rates were 77, 83, and 88% of roots colonized for the low, middle and high seeding rates, respectively. All densities for both crops exhibited high AMF colonization levels.

4.3.2 Phosphorus concentration and uptake

Trends in P concentration for field pea in the growth chamber experiment varied between treatments (Fig. 4.4). The lowest seeding rate showed a steady increase in the P concentration in the plant tissue at each successive sampling time until a plateau was reached at 3.5 mg g^{-1} 40 DAE. The medium plant density reached a peak at 4.7 mg g^{-1} 30 DAE, and then decreased at the fourth and fifth harvests. The P concentration for the highest plant density decreased from the second to the fifth harvest, at which time the medium and high plant densities showed similar P concentrations (2.5 mg g^{-1}) in aerial biomass.

Phosphorus uptake per plant was similar for all three treatments for the first three harvests, then significantly different between all seeding rates at the fourth and fifth harvests (40 and 50 DAE). The final values for P uptake per plant 50 DAE were 93.4, 50.2, and 24.4 mg P $plant^{-1}$ for the low, medium and high seeding rates, respectively.

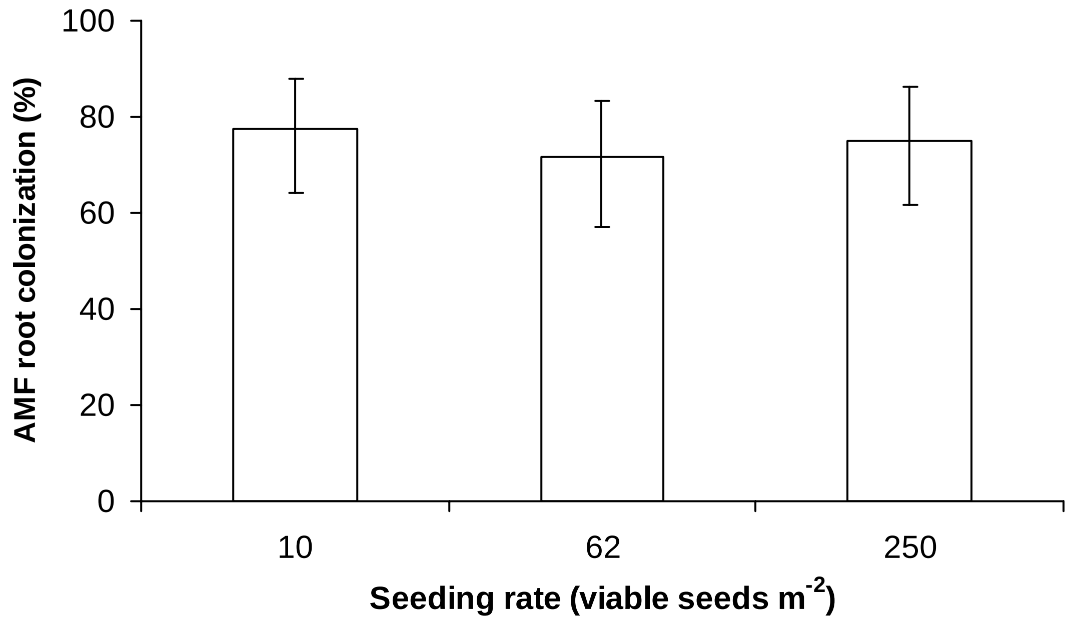

Fig. 4.2 Impact of seeding rate on root colonization by AMF in organic field-grown field pea. Data combined for sites in central Saskatchewan in 2005 and 2006. Bars indicate one standard error of the mean. Differences were not significant at $P \leq 0.05$.

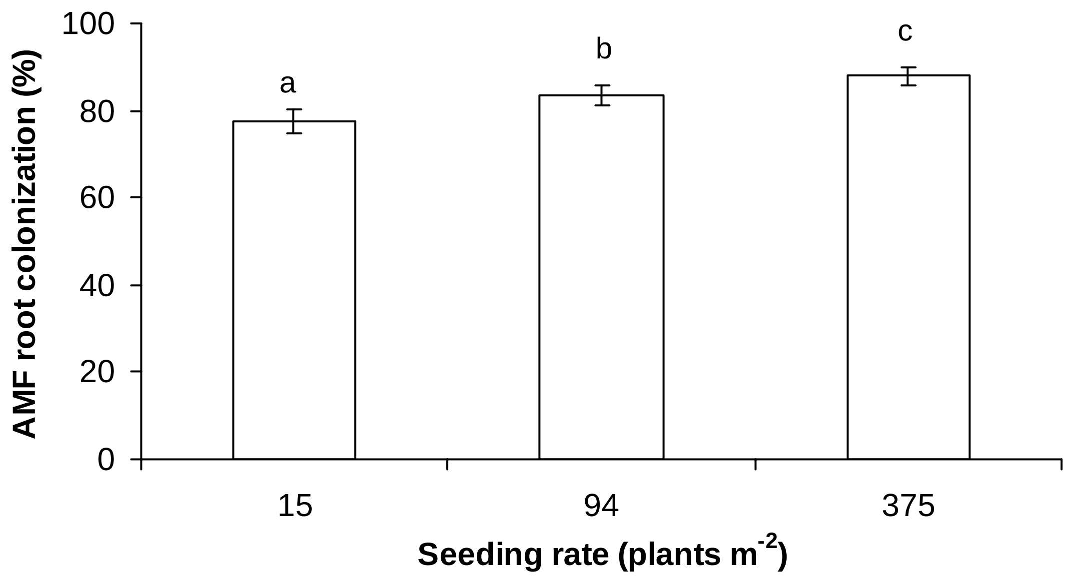

Fig. 4.3 Impact of seeding rate on root colonization by AMF in organic field-grown lentil. Data combined for sites in central Saskatchewan in 2005 and 2006. Bars indicate one standard error of the mean. Letters denote significant differences at $P \leq 0.05$.

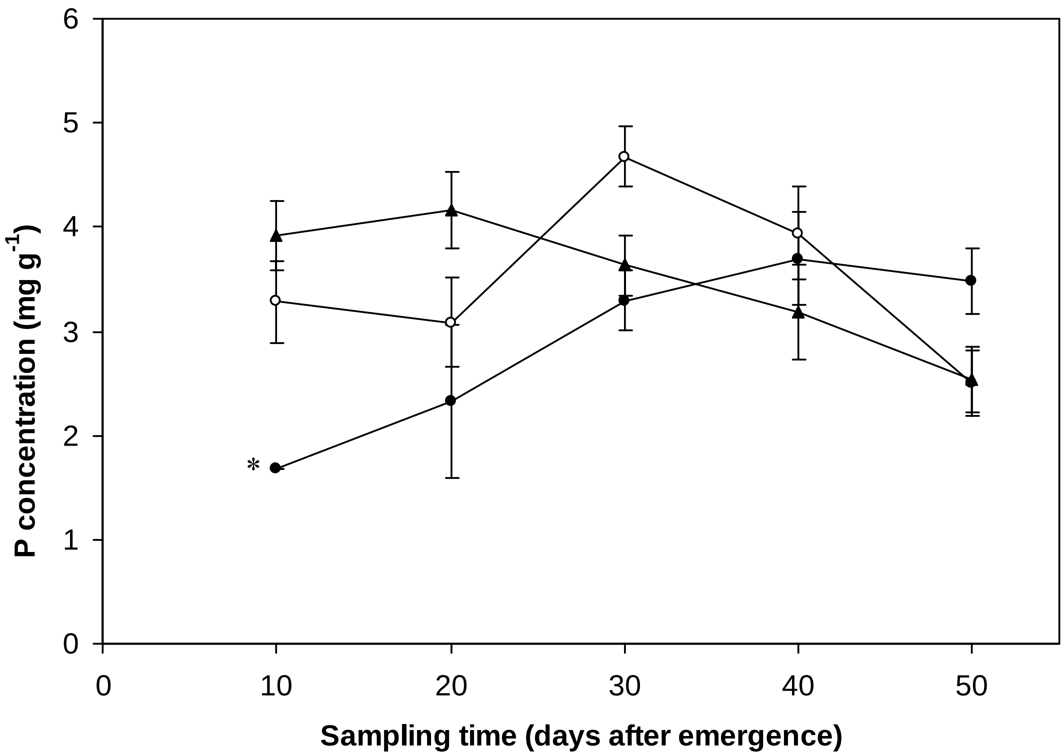

Fig. 4.4 Phosphorus concentration for field pea grown in organically-managed soil at five harvest dates (10, 20, 30, 40 and 50 DAE). Bars indicate one standard error of the mean. Plant densities are 1 plant pot^{-1} (●), 4 plants pot^{-1} (○) and 16 plants pot^{-1} (▲). *The data point for the first harvest of the lowest plant density is the result of combining all four reps to accumulate enough plant material for a single analysis and therefore error could not be calculated. This may not be a true representation of P concentration at the lowest plant density.

While the lowest plant density showed the highest P uptake per plant, the opposite occurred when assessing each pot. Total P uptake per pot increased with increasing plant density (Fig. 4.6). At the first harvest 10 DAE, most of the P uptake measured was likely supplied by the seed. At the final harvest, the highest plant density removed 385 mg P pot^{-1}, the medium density removed 200 mg P pot^{-1}, and the lowest density removed 105 mg P pot^{-1} in the aerial biomass. Phosphorus uptake per plant decreased with increasing plant density (Fig. 4.5).

Phosphorus removal per pot was significantly higher in the high density treatment for the first, second, and fifth harvest dates. At the third and fourth harvests, all treatments were significantly different at $P \leq 0.05$. The logistic curves fitted to the data were similar to those for P uptake per plant (Fig. 4.5) except that the curves representing the lowest and highest plant densities were reversed.

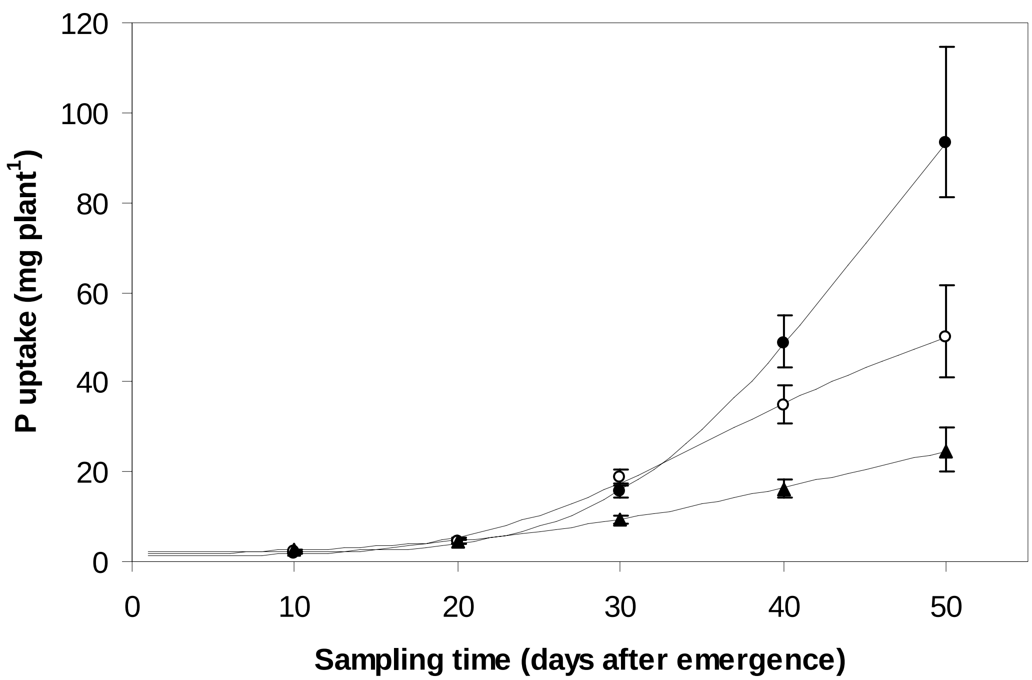

Fig. 4.5 Phosphorus uptake per plant by pea grown in organically-managed soil in a growth chamber at five sampling times. A four parameter logistic equation was fitted to the data for each plant density. Bars indicate one standard error of the mean. Plant densities are 1 plant pot^{-1} (●), 4 plants pot^{-1} (○) and 16 plants pot^{-1} (▲). The data point for the first harvest of the lowest plant density was the result of combining all four reps to accumulate enough plant material for a single analysis.

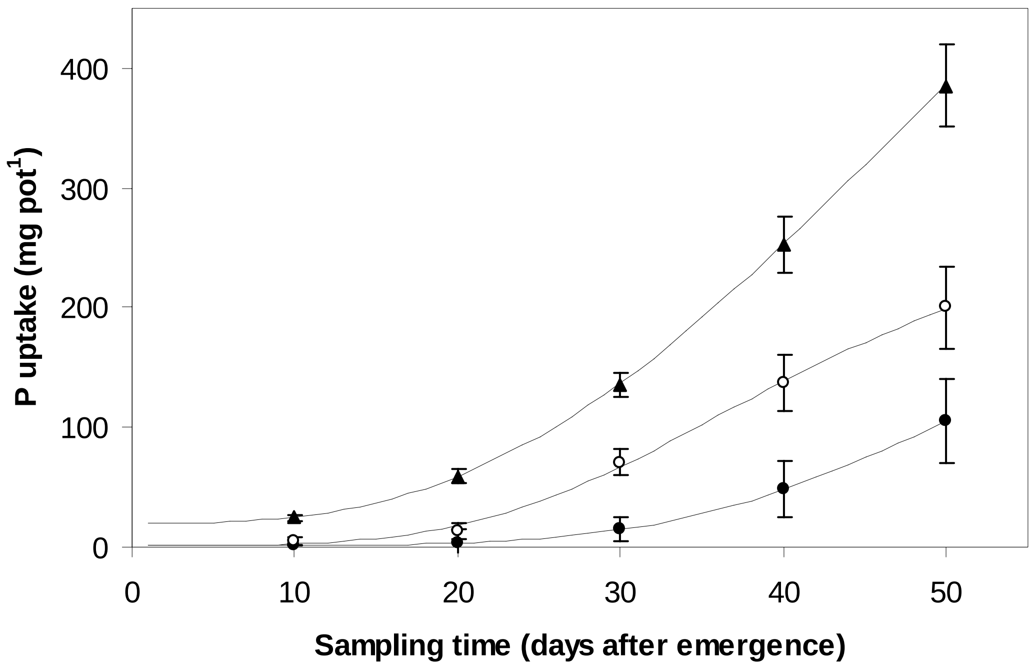

Fig. 4.6 Phosphorus uptake per pot by pea grown in organically-managed soil in a growth chamber at five sampling times. A four parameter logistic equation was fitted to the data for each plant density. Bars indicate one standard error of the mean. Plant densities are 1 plant pot^{-1} (●), 4 plants pot^{-1} (○) and 16 plants pot^{-1} (▲). The data point for the first harvest of the lowest plant density was the result of combining all four reps to accumulate enough plant material for a single analysis.

The upper asymptote and slope values for the 1 plant pot^{-1} treatment were higher than the 16 plant pot^{-1} treatment when comparing P uptake per plant (Table 4.3). The lower asymptote values (y_0) were similar between treatments. When comparing treatments in terms of P uptake per pot, again, the slope value was higher for the 1 plant pot^{-1} treatment than the 16 plant pot^{-1} treatment (Table 4.3). In this case, however, the upper asymptote value was much higher for the 16 plant pot^{-1} treatment than any other. Another finding for the P uptake per pot measurements was that the starting value for P uptake (y_0) was higher for the 16 plant pot^{-1} treatment than any other. This is not surprising as there were many more plants taking up P at the highest density than at the medium and low plant densities.

In the field experiment, there were no significant differences between treatments in P concentration for seed or straw in field pea or lentil (Table 4.4). There were differences, however, in P uptake. As seeding rates increased from 15 to 375 plants m^{-2}, seed P increased from 0.6 to 3.8 kg ha^{-1} and straw P increased from 0.05 to 1.7 kg ha^{-1} for lentil (Table 3.17). In field pea, seed P increased from 0.5 to 3.8 kg ha^{-1} and straw P increased from 0.2 to 2.7 kg ha^{-1} as seeding rate increased from 10 to 250 plants m^{-2}. (Table 3.10). The increases in P uptake were due to increased yield and biomass as seeding rate increased, as P concentrations did not vary significantly between seeding rates.

Table 4.3 Parameter estimates (±S.E.) for Equation 4.1 fitted to P uptake data for growth chamber pea biomass.

	Parameter estimates			
Pea density	a†	b‡	x_0§	y_0¶
P uptake per plant				
1 plant pot^{-1}	172.0 (20.72)#	-5.0 (0.36)	48.8 (2.32)	2.0 (0.63)
4 plants pot^{-1}	70.9 (17.94)	-3.9 (0.96)	41.0 (5.46)	1.4 (1.73)
16 plants pot^{-1}	65.5 (0.51)	-2.8 (0.01)	63.1 (0.29)	2.2 (0.01)
P uptake per pot				
1 plant pot^{-1}	272.1 (0.73)	-4.9 (0.01)	55.2 (0.01)	1.6 (0.01)
4 plants pot^{-1}	287.7 (71.21)	-3.9 (0.96)	41.0 (5.32)	1.7 (6.91)
16 plants pot^{-1}	976.6 (87.85)	-2.9 (0.10)	59.6 (3.15)	19.8 (1.56)

† upper asymptote of P uptake

‡slope factor that describes how quickly P is increasing in the plant

§days after emergence where one-half of P uptake is achieved

¶lower asymptote of P uptake

#± Standard error in parentheses

Table 4.4 Phosphorus concentrations in seed and straw for organic field pea and lentil grown in the field at various seeding rates combined for 2005 and 2006.

Crop	Seeding rate (viable seeds m^{-2})	Seed P ($mg\ kg^{-1}$)	Straw P ($mg\ kg^{-1}$)
Field pea	10	2307	652
	62	2209	635
	250	2218	726
Lentil	15	2781	430
	94	2738	359
	375	2917	597
Diff. of LS means†		NS‡	NS

†Difference of least squares means
‡Not significant at $P \le 0.05$

4.3.3 Influence of non-host weeds on AMF colonization

The proportion of the weed community made up by non-AMF weeds did not change significantly between seeding rates for either field pea or lentil in the field experiment (Table 4.5). There were differences in the biomass produced by non-host weeds between crops, however. The mean proportion of non-host weeds was approximately 30% for lentil and over 50% for field pea (Table 4.5).

Table 4.5 Proportion of weeds that do not host AMF in an organic field study of field pea and lentil combined for sites in central Saskatchewan in 2005 and 2006.

Seeding rate	Proportion of non-host weeds
(viable seeds m^{-2})	(%)
Field pea	
10	52
62	64
250	49
Diff of LS means†	NS‡
Lentil	
15	30
94	30
375	34
Diff of LS means	NS

† Differences between least squares means
‡ Not significantly different at $P \leq 0.05$

4.4 Discussion

Arbuscular mycorrhizal fungi colonized approximately 80% of crop roots in our experiments. Colonization rates recorded by other researchers have found similar or lower maximum colonization levels. Inoculated field bean roots were 80% colonized by AMF in a growth chamber experiment (Kucey and Bonetti, 1988). Arbuscular mycorrhizae colonized approximately 75% of plant roots 50 days after field pea seedling emergence (Jakobsen and Nielsen, 1983). Lower colonization rates were reported by Ryan and Angus (2003), where only 20 to 50% of roots were colonized, and 30 to 60% of wheat roots showed AMF colonization. Sanders et al. (1977) found that between 50 and 60% of onion roots were colonized 49 days after sowing.

There is considerable research that has shown a reduction in AMF colonization as plant density increases (Jakobsen and Nielsen, 1983; Koide and Dickie, 2002; Shroeder and Janos, 2005). Jakobsen and Nielsen (1983) found that as root density increased, AMF infection levels decreased from 80% to 30% in barley. Shroeder and Janos (2005) found a negative correlation between mycorrhizal colonization and plant density of *Capsicum annuum* and *Zea mays* grown in pots in a growth chamber experiment similar in methodology to ours. Shroeder and Janos (2005) and Abbott and Robson (1984) suggest that the reason for reduced benefits of AMF at high plant densities was a reduction in the cost/benefit ratio in supplying the AMF with carbon in exchange for increased P uptake. A study by Abbott and Robson (1984) found that root length infected by AMF was lower for the highest density of subterranean clover than the other densities 19 DAP in a growth chamber experiment. The percentage of root length infected at 38 DAP, however, was similar for all densities. In another experiment using *Trifolium subterraneum* (clover) as the test crop, the highest plant density (25 plants pot^{-1}) had the highest level of colonization by AMF 30 DAP (Abbott and Robson, 1984). Similarly, Warner and Mosse (1982) found that increasing clover density increased the rate of spread from a central point, and that AMF colonization of roots was more evenly spread in higher density treatments than in low density ones. The study by Warner and Mosse (1982) may have limited application in this case because our study used soil with existing inoculum that would have been evenly spread throughout the pot. Abbott and Robson (1984) found that mixing the inoculum throughout the pot resulted in a higher percentage of root colonization than if the inoculum was placed in a specific location, although colonization occurred at a slower rate. The high level of colonization associated with our study may have been due to the relatively even distribution of inoculum in the soil.

The results of our lentil study are consistent with the findings of Warner and Mosse (1982) and Abbott and Robson (1984), as percentage of root colonized by AMF generally increased with higher plant densities. The high rate of variability in colonization levels within the field pea plots resulted in no differences between seeding rates in the field, but in the growth chamber, field pea also exhibited increased AMF colonization of roots at higher plant densities. Warner and Mosse (1983) found that hyphae from AMF could colonize roots up to 20 mm away from a colonized root. Root density of plants able to be colonized by AMF was much higher in the high density treatments in the field and growth chamber, and colonization levels may have been increased due to the close proximity of roots in these treatments.

The level of AMF colonization for field pea in the growth chamber experiment was not different between seeding rates early in plant growth (Fig. 4.1). No previous research studying the rate of AMF colonization for various seeding rates could be found. There are some studies, however, that have determined colonization rates at various times during the growing season that may be used as a comparison, as the rate of colonization was not different between seeding rates between 10 and 30 DAE. The level of AMF colonization reached in the growth chamber study 30 DAE ranged from 60 to 70%. Schweiger et al. (2001) found that pea colonization levels reached 66% in their growth chamber study 43 DAP. In a low-input study, Galvez et al. (2001) found that 40 to 60% of maize roots were colonized by AMF. Seedlings were less likely to encounter intraspecific competition for P as root systems were smaller and the soil was still somewhat unexplored (Koide and Dickie, 2002).

The soil used for the growth chamber was low in P and the high plant densities may have relied upon the association with AMF to acquire more soil P than the low plant density. Plants grown in soil high in P generally have lower levels of colonization by AMF (Mosse et al., 1981). Galvez et al. (2001) found that the colonization potential was higher in soils where the P concentration was lower.

Despite higher colonization at higher plant densities in the growth chamber experiment, P concentration decreased as plant density increased. The results of this study indicate that availability of AMF for root colonization is not a limiting factor in this particular soil. In this case, a potential reduction in plant-available nutrients, especially P, may have increased the rate and level of AMF colonization of plant roots. The steady level of AMF colonization for the low plant density between 30 and 50 DAE indicated that the plant was able to access enough P for growth and did not require further colonization by AMF for that purpose. The medium and high plant densities, however, increased AMF colonization another 20% beyond the highest level of colonization of the low density. Phosphorus deficiencies may have resulted in higher colonization for those treatments, as total P uptake per pot for the medium and high densities were higher than for the low density.

When P uptake per pot was converted to P uptake in kg ha^{-1}, the amount of P removed by aerial biomass alone would have been 60, 31, and 16 kg P ha^{-1} for the high, middle, and low densities. The lowest plant density of one plant pot^{-1} would have had ample access to available soil P based on uptake in aerial biomass and the soil test prior to beginning the experiment, and so P was likely not limiting for that density. The two highest densities would have required more available P than the soil provided according to the soil test at the initiation of the experiment (27 kg ha^{-1}). Phosphorus concentrations per plant at these densities were also lower, and P may have been limiting. Access to other forms of P in the soil may have been required for continued crop uptake and growth. Bolan et al. (1987) reported that AMF can obtain P from other forms, such as iron phosphate, than the readily-available phosphate anions HPO_4^{2-} and $H_2PO_4^-$ (Richardson, 2001). Colonization levels in our experiment may have increased to increase P uptake from other sources of soil P. Chen et al. (2005) found that two of the three plant species tested showed a positive correlation between AMF colonization and P concentration in plant biomass. Ryan and Angus (2003), however, found that colonization level by AMF was not correlated to P uptake in field pea or wheat even when soil P was low (11 mg kg^{-1}). In our field experiment, there was no correlation between AMF colonization and P concentration in either field pea or lentil, and the soil P levels ranged between 3.3 and >30 mg kg^{-1}. In the growth chamber experiment, P concentration and P uptake per plant decreased at high densities, even though AMF colonization increased.

There was no correlation in the field study between AMF colonization level or seeding rate and proportion of non-host weed biomass (Table 4.5). Other researchers have found that the presence of weeds that do not host AMF can decrease the colonization levels in crop plants (Feldmann and Boyle, 1999). Chen et al. (2005) found that poorly mycorrhizal species had no effect or a negative effect on the AMF colonization of highly mycorrhizal species as compared to their growth in a monoculture. Reduction in AMF colonization due to the presence of poorly mycorrhizal species was approximately 5%. Conversely, Fontenla et al. (1999) found that AMF colonization of pea was higher with non-hosts present than alone (65 and 73%, respectively), and that non-hosts did not inhibit AMF unless they established before the crop. In fact, in the presence of mycorrhizae, the non-host weed lambsquarters exhibited a lower relative growth rate and lower survivorship than in the absence of AMF (Francis and Read, 1995). Our study did not find any effect of non-host weeds on AMF colonization of crop plants.

The differences between the proportion of non-host weeds between field pea and lentil may be a function of the differing growth characteristics of the crops rather than AMF colonization, as colonization levels by AMF were similar for the two crops in the field. All of the non-host weed species were broadleaved weeds and when weeds were separated into grassy and broadleaved species, the proportion of biomass in broadleaved weeds was also higher for field pea than lentil. As suggested in Chapter one (section 3.4), field pea may be more competitive with grassy weeds than broadleaved weeds due to the morphology of the plant, allowing for a greater proportion of broadleaved weeds to establish, whereas lentil is less competitive and may not suppress either type of weed well.

4.5 Conclusions

Colonization of lentil by AMF increased as seeding rate increased but there was no appreciable difference in the level of colonization of field pea in the field. Field pea did, however, show an increase in the level of AMF colonization as seeding rate increased in a growth chamber experiment. The rate of AMF colonization as determined by field pea in the growth chamber did not differ between seeding rate treatments during early growth (0 to 30 DAE) indicating that P likely was not limiting at that time. The total colonization levels reached, however, differed substantially at 50 DAE. The higher plant densities (4 and 16 plants pot^{-1}, equivalent to 62 and 250 plants m^{-2} in the field) had significantly higher AMF colonization. Higher density pea treatments had lower concentrations of P despite higher colonization levels in the growth chamber experiment, indicating that P was limiting at later harvests. Phosphorus concentrations at harvest in the field did not differ for field pea and lentil between crop densities.

The difference in results between the field and growth chamber were likely due to the constraints of the pot experiment in terms of the quantity of soil available for roots to explore. The field experiment offered a greater quantity of soil for root exploration and nutrient uptake, and field pea and lentil in a field situation may have had greater access to nutrients than those confined to pots in a growth chamber. However, weeds may have decreased P availability in the field, increasing the AMF colonization level for all seeding rates to access P and reducing the ability of the crop to access sufficient P at lower colonization levels for low seeding rates.

High densities of organic field pea and lentil may require more AMF colonization to acquire sufficient amounts of soil-immobile nutrients (especially P) as lower seeding rates. This was shown in our field experiment, as P concentrations were similar despite plant density, while AMF colonization increased with increasing density in most cases.

Further research to determine the contribution of roots to P uptake would be beneficial in an assessment of the total amount of P taken up by plants and how it relates to AMF colonization.

5. ECONOMIC OPTIMUM SEEDING RATES FOR ORGANIC PRODUCTION OF FIELD PEA AND LENTIL

5.1 Introduction

Current seeding rate recommendations for field pea and lentil have been determined under conventional management systems. Saskatchewan Pulse Growers (2000) suggest densities of 88 plants m^{-2} for field pea and 130 plants m^{-2} for lentil in western Canada. However, seeding rates to optimize production of these crops in organic systems have not been determined for this region. Studies conducted in other countries suggest that seeding rates should be increased beyond those developed for conventional production to suppress weeds. An organic production study in France found that field pea populations greater than 80 plants m^{-2} decreased weed densities (Corre-Hellou and Crozat, 2005). An Australian study in pesticide-free conditions determined that the optimal crop density for lentil was 150 plants m^{-2} and could be higher (up to 230 plants m^{-2}) where unfavourable growing conditions exist (Siddique et al., 1998). McDonald et al. (2007) recently found that increasing lentil density from 50 to 200 plants m^{-2} increased yield and decreased weed biomass in Australia.

The profitability of organic crops is highly dependent upon price premiums which can be highly variable over time (Smith et al., 2004). For example, the University of Saskatchewan (2006) reported that the price paid for organic lentil ranged from \$0.88 to \$1.98 per kg (University of Saskatchewan, 2006). While increasing seeding rate may increase the competitive ability of the crop, the profitability of the crop may or may not increase, as the cost of the seed must be taken into consideration. Pulse seed in particular can be prohibitively expensive when increasing seeding rates (Loss et al., 1998).

Previous analyses have used various methods to determine economic optimum seeding rate. The most common method was developed by French et al. (1994), where non-linear regression was fitted to describe the yield-density response, and then the slope where the optimal return was reached was determined and the ideal density identified. This method has been used in a number of studies (Loss et al., 1998; Jettner et al., 1999). Shirtliffe and Johnston (2002) fit non-linear regression equations to dry bean gross return (minus seed cost) and density. Economic optimum plant densities were determined from the density where return was maximized (Shirtliffe and Johnston, 2002). A similar method was used by Norsworthy and Oliver (2001) where variable seed and weed management costs were subtracted from gross returns, then plotted against seeding rate. Again, the economic optimum seeding rate was determined to be the density where gross profit was maximized.

5.2 Materials and Methods

5.2.1 Site description and plot management

Sites were chosen on existing organic farms near Vonda, Vanscoy and Delisle, SK. Sites descriptions are provided in Sections 3.2.1 and 3.2.2.

Field pea and lentil were seeded at rates of 10, 25, 62, 156 and 250 plants m^{-2} and 15, 38, 94, 235 and 375 plants m^{-2}, respectively. Further information regarding plot management and sampling is provided in Sections 3.2.1 and 3.2.2.

5.2.2 Economic analysis

To determine the profitability of each seeding rate, an equation was used to calculate the potential return:

$$R = (Y * PR) - (SW * C) \qquad [5.1]$$

where R=return (\$ ha^{-1}), Y=seed yield (kg ha^{-1}), PR=price received, SW=seed weight planted (kg ha^{-1}) and C=seed cost (\$ kg^{-1}).

Return was calculated by subtracting the variable costs from the gross profit (Norsworthy and Oliver, 2001). Variable costs were determined to be the cost of purchasing seed, as fertilizers and chemical pesticides are not permitted for organic production.

The cost of seed was provided by an organic seed supplier near Saskatoon, SK (Marysburg Organic Producers, Inc., p. comm.). The seed costs used were \$0.84 kg^{-1} for lentil and \$0.27 kg^{-1} for field pea. The seed weight planted was determined from the 1000 seed weight for each crop as provided by the Saskatchewan Seed Growers Association (2006) multiplied by the number of seeds planted for each seeding rate. The number of seeds planted depended upon the percent germination, as described in Section 3.2.1.3.

The gross profit was determined from the mean selling price for each crop in Saskatchewan averaged for 2005 and 2006 as reported by the University of Saskatchewan (2006). The mean selling prices for lentil in 2005 and 2006 were \$1.32 and \$0.77 kg^{-1}, respectively. The mean selling prices for field pea in 2005 and 2006 were \$0.32 and \$0.25 kg^{-1}, respectively. The average selling prices used were \$1.05 kg^{-1} for lentil and \$0.28 kg^{-1} for field pea.

5.2.3 Statistical analysis

Data were analyzed using the PROC MIXED procedure in SAS (SAS Institute Inc., 2004). Sites and years were combined, as the site-year*treatment interaction was not significant at $P \leq 0.05$. Profit data were square-root transformed to meet the assumption of homogeneity of variance and the back-transformed data were presented. Site-year and block were treated as random effects.

A non-linear regression model was fitted to the means of the return data at each site using the PROC NLIN procedure of SAS (SAS Institute Inc., 2004). For both the lentil and field pea data, the two-parameter Michaelis-Menten model used to describe dose-response relationships was used with a modification of parameters (Jolliffe et al., 1984):

$$Y = R_{\max} \times D / (D_{50} + D) \quad [5.2]$$

where R_{max} = maximum return (\$ ha^{-1}), D_{50} = the crop density at which half of R_{max} occurs (plants m^{-2}), and D = seeding rate (plants m^{-2}). This model was chosen to describe the data because it provided a good fit to the data and biologically meaningful parameters.

For combined field pea data as well as the Delisle 2005 field pea data, a modified Michaelis-Menten equation was fitted. This equation is algebraically equivalent to the yield-density equation by Firbank and Watkinson (1990). This re-parameterized equation accounted for the decrease in return at the highest seeding rate:

$$Y = R_{\max} * D * [(D_{50} + D)^{-c}] \qquad [5.3]$$

where R_{max}= upper asymptote (\$ ha^{-1}), D=seeding rate (plants m^{-2}), D_{50}=the seeding rate at which half of the upper asymptotic value would be reached (plants m^{-2}) and c=constant. The optimal seeding rate for each crop was determined empirically where an asymptote was reached for return, as the parameters used in this equation were not biologically meaningful.

5.3 Results

5.3.1 Field pea

Field pea yield increased to the highest seeding rate. Conversely, potential net return decreased by approximately \$2 between seeding rates of 156 and 250 plants m^{-2}, although the two rates of return were very similar (Fig. 5.1).

Potential return peaked at \$271 at a seeding rate of 200 plants m^{-2} therefore this seeding rate may be considered to be the optimal seeding rate for organic production of field pea in the central region of Saskatchewan. When divided by site, there were no significant differences between values for maximum return, but the parameter estimates had a lot of variability associated with them (Table 5.1). Maximum return varied between \$237 ha^{-1} at Delisle in 2005 and \$320 ha^{-1} at Vonda in 2006. The two-parameter Michaelis-Menten model was fitted to all but the combined data for sites and years as well as the Delisle 2005 data (Fig 5.2, 5.3). For those datasets, the three-parameter model was a better fit as it described the reduction in return at high plant densities. The Vanscoy 2006 site also showed a reduction in return at high densities, but the two-parameter model provided a better fit at this site (Fig. 5.3).

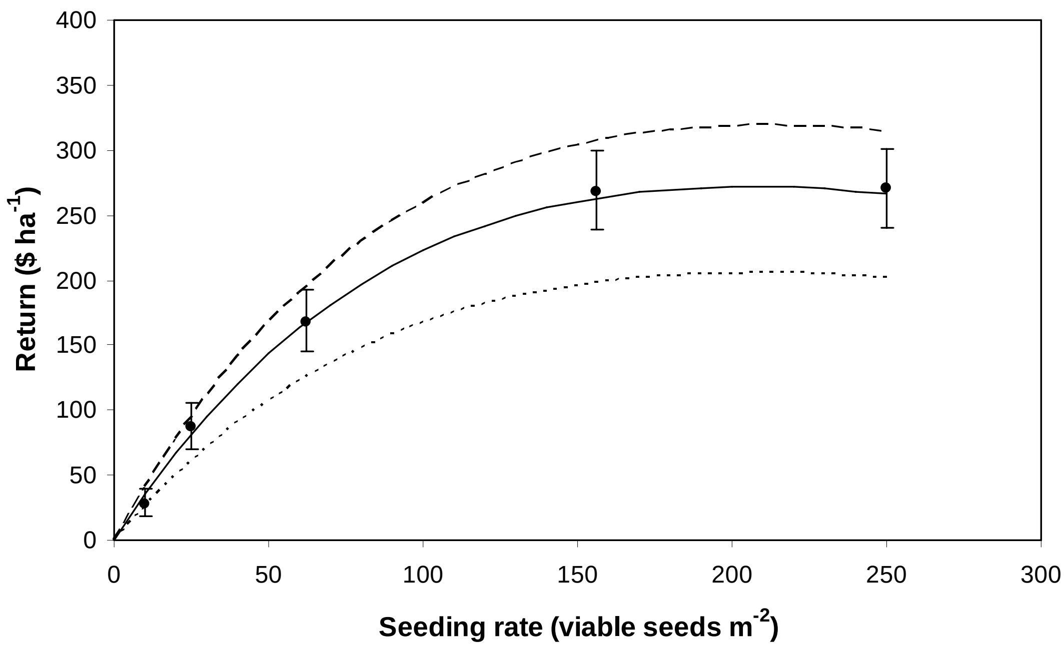

Fig. 5.1 Return for organic field pea combined for sites in central Saskatchewan in 2005 and 2006. Bars indicate one standard error of the mean. Regression lines indicate average price received (—), 2005 selling price (---), and 2006 selling price (…).

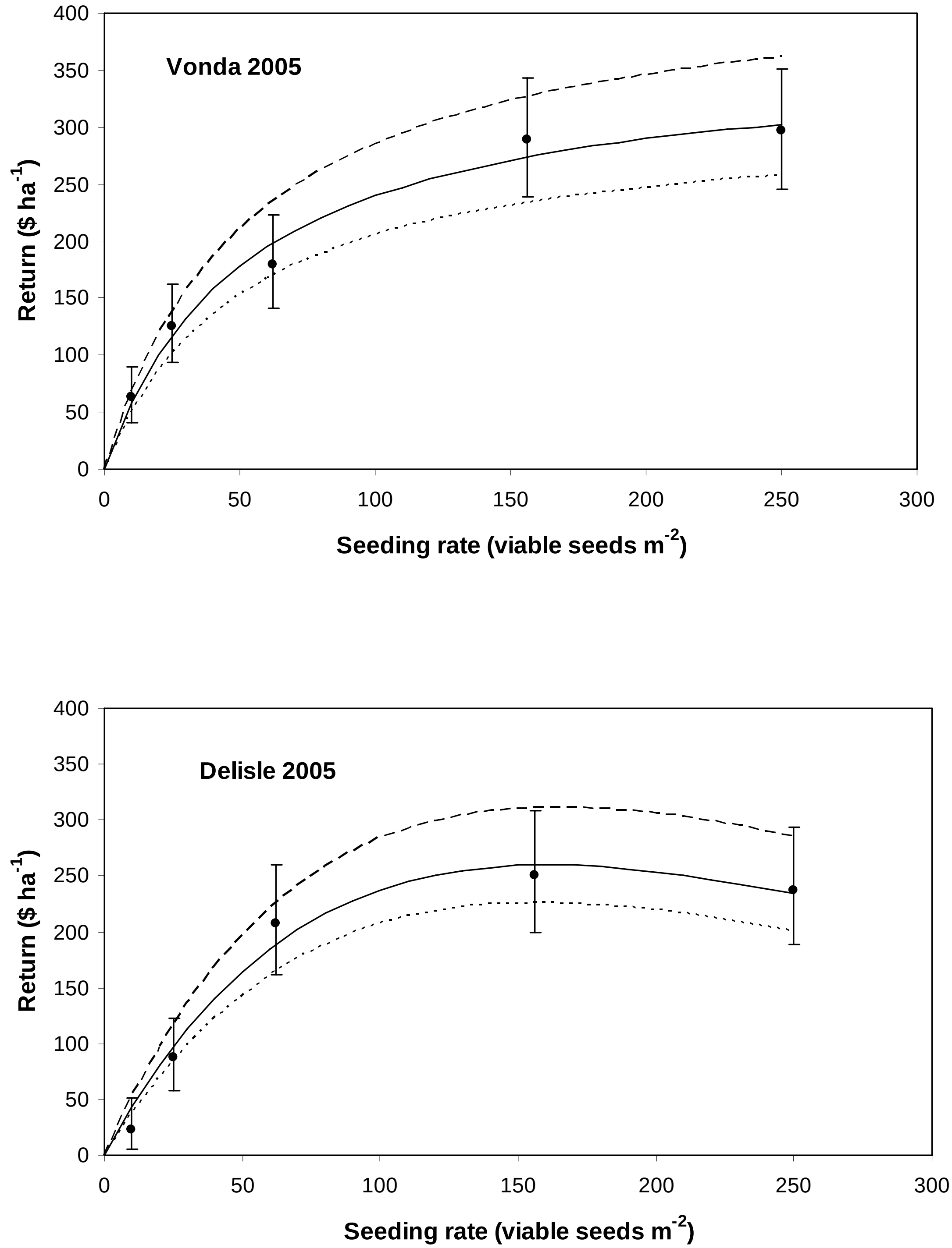

Fig. 5.2 Return for organic field pea by site for Vonda and Delisle in 2005. Bars indicate one standard error of the mean. Regression lines indicate average price received (—), 2005 selling price (---), and 2006 selling price (…).

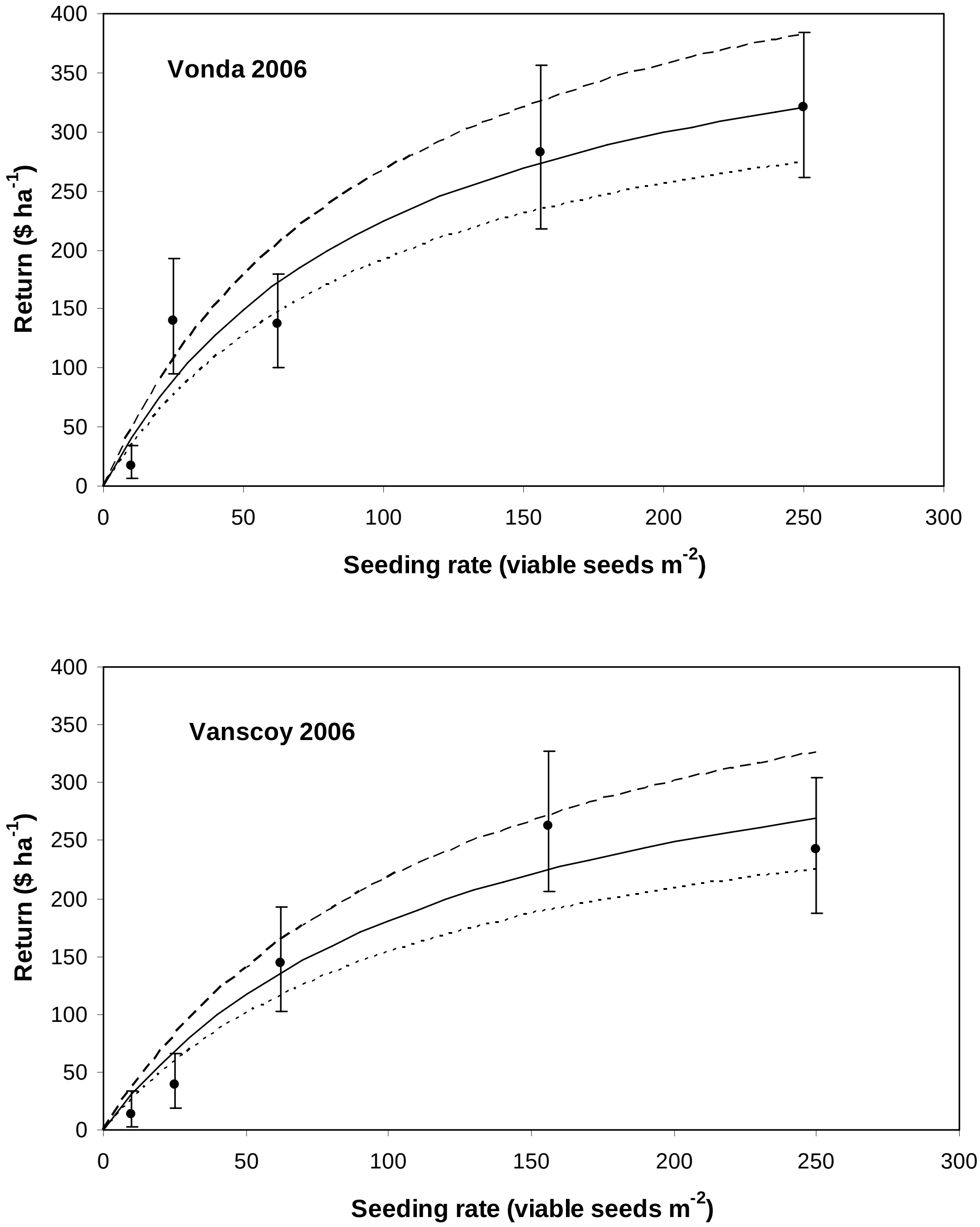

Fig. 5.3 Return data for organic field pea by site for Vonda and Vanscoy in 2006. Bars indicate one standard error of the mean. Regression lines indicate average price received (—), 2005 selling price (---), and 2006 selling price (…).

Table 5.1 Parameter estimates (±S.E.) for organic field pea returns for each site and combined for all sites in Saskatchewan in 2005 and 2006.

Site	Parameter estimates			
	R_{max} †	D_{50} ‡	c§	R^2
	($\$ ha^{-1}$)	(viable seeds m^{-2})		
Combined¶	$9.8*10^{75}$ (0) #	4078 (127) ††	20.89 (0.08)	0.99
2005				
Vonda	367 (24)	53 (11)		0.98
Delisle	$5.58*10^{42}$ ($4.09*10^{45}$)	1894 (13506)	12.84 (85.01)	0.94
2006				
Vonda	449 (107)	100 (57)		0.90
Vanscoy	398 (114)	120 (77)		0.91

† Maximum return achieved

‡One-half of maximum return achieved

§Constant

¶Equation used for the combined site and Delisle 2005 return data used three parameters (Equation 5.3), as the model provided a better fit than the two-parameter Michaelis-Menten equation (Equation 5.2)

Where the three-parameter model is used, the values for R_{max} and D_{50} are not meaningful

††± Standard error in parentheses

For the combined analysis, the seed cost increased by \$56 ha^{-1} between the two highest seeding rates and resulted in a slight overall decrease in return, even though yield increased between these two seeding rates (Table 5.2).

Emergence rates were lower than the seeding rates, and the actual plant density achieved at the recommended seeding rate of 200 seeds m^{-2} was approximately 120 plants m^{-2} (Table 5.2).

A scenario based on a seed cost equal to the selling price was also assessed. In this scenario, profit peaked at the highest seeding rate (250 seeds m^{-2}) with a return of \$266 ha^{-1}, however, the difference between seeding rates of 156 seeds m^{-2} and 250 seeds m^{-2} was +\$0.40 ha^{-1}. The producer would be unlikely to increase seeding rates by almost 100 seeds m^{-2} for an additional profit of \$0.40 ha^{-1}, so the optimal seeding rate in this case would be approximately 156 seeds m^{-2}.

Table 5.2 Yield and profitability of organic field pea grown in Saskatchewan combined for sites in 2005 and 2006.

Seeding rate		Emergence	Yield	Seed cost	Return
(seeds m^{-2})	(kg ha^{-1})	(plants m^{-2})	(kg ha^{-1})	(\$ ha^{-1})	(\$ ha^{-1})
10	22	6	209	5.93	28.22
25	55	13	491	14.84	87.31
62	136	41	973	36.79	168.05
156	343	102	1460	92.57	268.43
250	549	146	1725	148.35	270.15

5.3.2 Lentil

Lentil yield followed a similar pattern to field pea in that it increased up to the highest seeding rate. Potential return continued to increase to the highest seeding rate up to \$952.54 ha^{-1} (Fig. 5.4). This seeding rate may be considered the optimal seeding rate for organic production of lentil in central Saskatchewan. The data, however, did not reach an asymptote, so yield and return may increase beyond the seeding rates used in this study. The seed cost, however, would also increase and farmers are unlikely to spend more to achieve a slightly higher return. The return lines on Fig. 5.4 indicated the variability associated with selling price during a two-year time period (2005 to 2006).

When divided by site, there were no significant differences between values for maximum return, but the parameter estimates had considerable variability associated with them (Table 5.3). Maximum return varied between \$2049 ha^{-1} at Vanscoy in 2006 and \$1054 ha^{-1} at Vonda in 2006. The two-parameter Michaelis-Menten model was fitted to all sites (Fig 5.5, 5.6).

The individual sites had higher maximum returns than the combined model in some cases. For example, Vonda in 2005 and Vanscoy in 2006 both had significantly higher R_{max} values than the combined site R_{max}. The Vanscoy site, however, showed poor emergence and the estimates for R_{max} may have had error associated with it as the data were still increasing and did not reach the asymptote (Fig. 5.6).

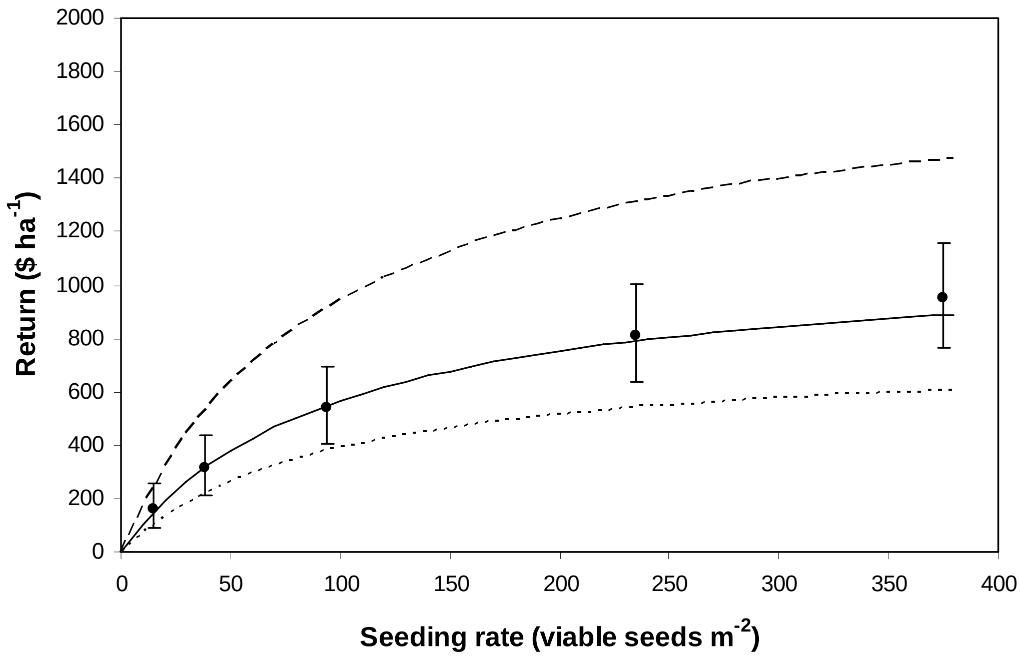

Fig 5.4 Lentil return combined for sites in central Saskatchewan in 2005 and 2006. Bars indicate one standard error of the mean. Regression lines indicate average price received (—), 2005 selling price (---), and 2006 selling price (…).

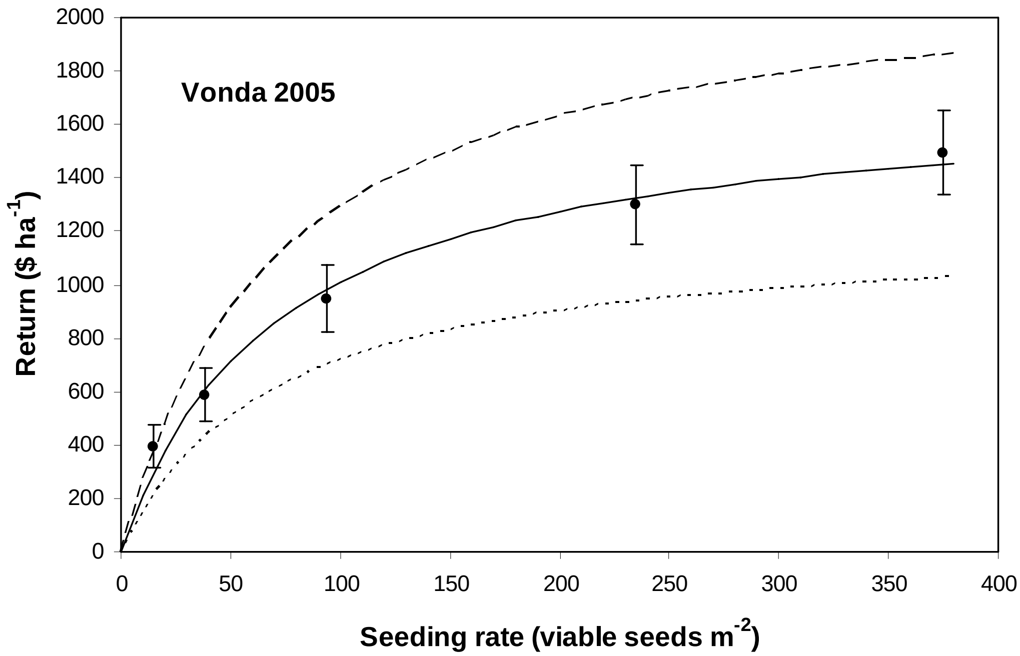

Fig. 5.5 Return data for organic lentil by site for Vonda and Delisle in 2005. Bars indicate one standard error of the mean. Regression lines indicate average price received (—), 2005 selling price (---), and 2006 selling price (…).

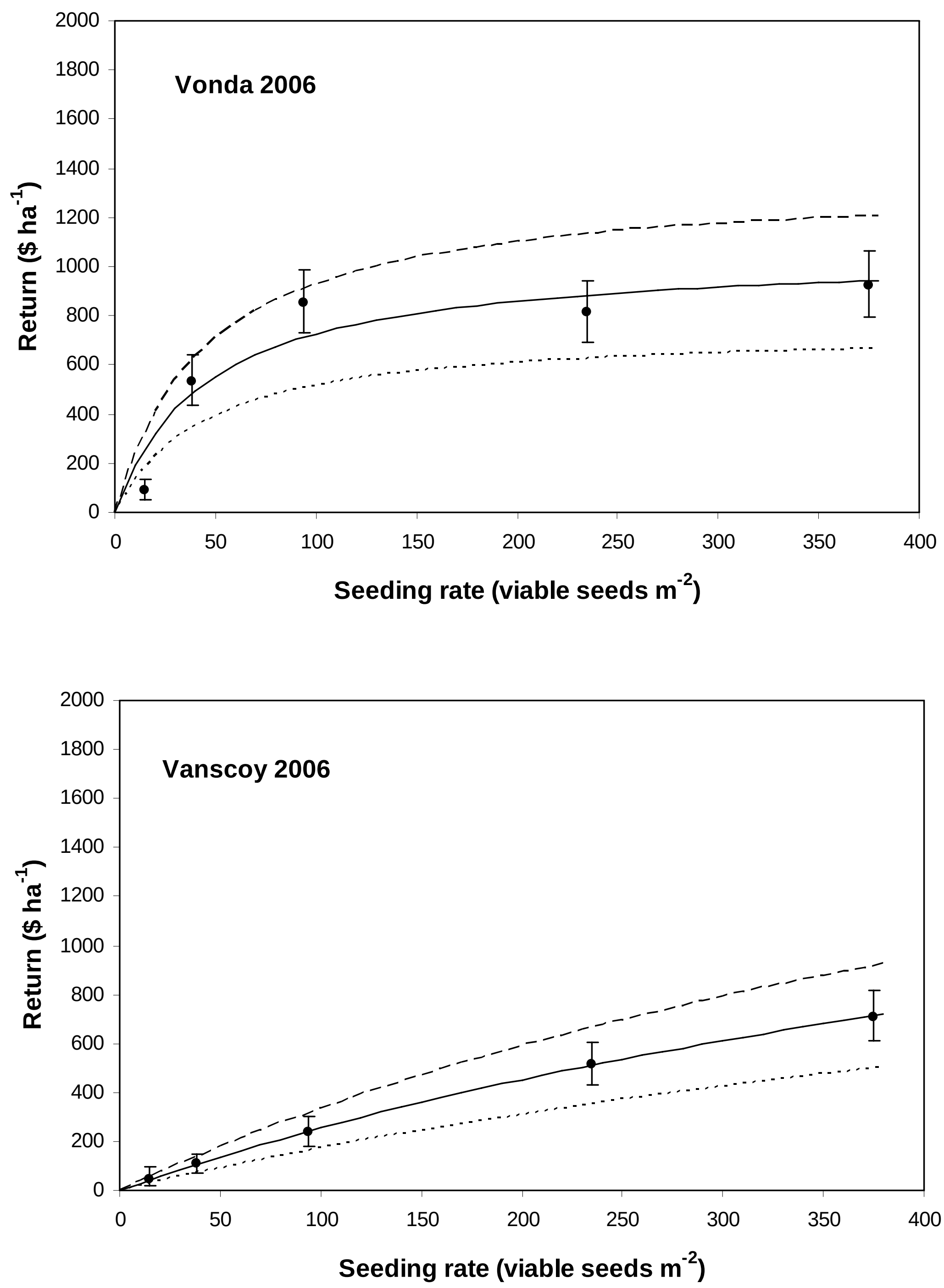

Fig. 5.6 Return data for organic lentil by site for Vonda and Vanscoy in 2006. Bars indicate one standard error of the mean. Regression lines indicate average price received (—), 2005 selling price (---), and 2006 selling price (…).

Table 5.3 Parameter estimates (±S.E.) for organic lentil returns for each site in 2005 and 2006.

Site	Parameter estimates		
	R_{max} †	D_{50} ‡	R^2
	$ ha^{-1}	Viable seeds m^{-2}	
Combined	1224 (42)§	114 (10)	0.99
2005			
Vonda	1724 (97)	71 (12)	0.98
Delisle	1107 (295)	162 (101)	0.86
2006			
Vonda	1054 (163)	45 (25)	0.83
Vanscoy	2049 (103)	706 (50)	0.99

†Maximum return achieved
‡Seeding rate where one-half of the maximum return achieved
§± standard error in parentheses

Yield increased to the highest seeding rate (Table 5.4). Seed cost increased to \$208 ha^{-1} at the highest seeding rate, which may be prohibitively expensive for some organic farmers (Table 5.4).

Emergence rates were lower than the seeding rates, and the actual plant density achieved at the recommended seeding rate of 375 seeds m^{-2} was approximately 184 plants m^{-2} (Table 5.4).

The yield and net return data indicate that the higher the seeding rate for organic lentil, the greater the yield and revenue potential, and the greater the reduction in weed biomass. The optimal seeding rate for organic production of lentil is much higher than the recommended rate for conventional production of 130 plants m^{-2}.

In the alternative scenario where seed cost equaled price received, the optimal seeding rate was the same at 375 seeds m^{-2}. At this seeding rate, the return was \$924 ha^{-1}.

Table 5.4 Yield and profitability of organic lentil grown in Saskatchewan combined for sites in 2005 and 2006.

Seeding rate		Emergence	Yield	Seed cost	Return
(seeds m^{-2})	(kg ha^{-1})	(plants m^{-2})	(kg ha^{-1})	(\$ ha^{-1})	(\$ ha^{-1})
15	10	10	200	8.32	163.50
38	25	20	423	21.07	315.14
94	62	62	706	52.12	539.67
235	155	129	1083	130.30	810.39
375	247	184	1291	207.92	952.54

5.4 Discussion

For both field pea and lentil, weed biomass decreased to the highest plant density (Fig. 3.1; 3.3). Harvest index decreased slightly at the highest plant densities, but grain yield continued to increase to the highest plant density (Table 3.8; 3.15). Soil nutrient levels and seed quality were not significantly affected by seeding rate for most sites (Table 3.11; 3.18). Arbuscular mycorrhizal fungi colonization increased as seeding rate increased for lentil but not field pea, although the level of colonization was high for all seeding rates for both crops (Fig. 4.2; 4.3). Most parameters measured were not negatively affected by seeding rate; therefore organic producers may increase seeding rates of field pea and lentil without negative implications to the system.

Field pea returns peaked at approximately 200 plants m^{-2}; this may be considered to be the economic optimum seeding rate for field pea grown in an organic production system. At this seeding rate, the yield was 1600 kg ha^{-1} and seed cost was approximately \$118 ha^{-1}. For seeding rates higher than 200 plants m^{-2}, yield increased slightly, but return decreased by approximately \$2. This organic seeding rate is 112 plants m^{-2} higher than the recommended rate for conventional production. The increase in seeding rate provided an additional 650 kg ha^{-1} in weed biomass reduction and approximately \$75 ha^{-1} more in profit. While the seeding rate was much higher than the recommended rate for conventional production, the actual plant density achieved was 32 plants m^{-2} higher at 120 plants m^{-2}, and the target plant density may be used by organic farmers with seeding rates adjusted to accommodate reduced germination and emergence.

Lentil returns increased to the highest seeding rate of 375 plants m^{-2}, but did not reach an asymptote with the plant densities used in this experiment. Yield also increased to the highest seeding rate. According to these data, the economic optimum seeding rate for organic production of lentil may be considered to be the highest seeding rate that is affordable to the producer. This organic seeding rate is 245 plants m^{-2} higher than the recommended rate for conventional production; however, the actual plant density achieved was only 50 plants m^{-2} higher at 184 plants m^{-2}. Increasing the seeding rate beyond the recommended rate for conventional production reduced weed biomass by an additional 700 kg ha^{-1} or 26%, and increased profit by approximately \$350 ha^{-1}. The target plant density of 184 plants m^{-2} may be used by organic farmers and seeding rates adjusted to account for emergence rates.

In the alternative scenario where seed cost equaled price received for the crop, the optimal seeding rate was lower for field pea (156 seeds m^{-2}), but no difference was noted for lentil. The highest returns were lower for both crops where seed cost was equivalent to selling price, but differences were slight (\$5.00 ha^{-1} for field pea and \$28 ha^{-1} for lentil). This alternative scenario emphasizes that seeding rates higher than those recommended for conventional production increase profits for organic production of field pea and lentil, despite increases in seed cost.

Seed cost may be prohibitive for very high seeding rates of legumes (Siddique et al., 1998). According to Siddique et al. (1998) seed costs are much higher for lentil than cereals and oilseeds, and may have a negative impact on profitability at higher seeding rates. Indeed, seed costs for organically grown lentil and pea are generally higher than selling prices, as seed cost includes the cost of seed cleaning, and organic selling prices ranged from \$0.22 to \$0.26 kg^{-1} for pea and \$0.88 to \$1.98 kg^{-1} for lentil in 2005 (University of Saskatchewan, 2006) Thus, organic growers may find that seed cost constrains their decisions to increase seeding rate.

Other issues surrounding the use of high seeding rates of field pea and lentil include the impact of seeding rate on equipment and labour. Seeding at very high rates increases the amount of seed running through the seeding equipment substantially and may cause blockages. This may, in turn, increase the amount of time required to seed the crop. Farmers are very busy in spring and the potential negative impact of seeding rate on the amount of time required to perform the task may be a consideration and should be mentioned.

Other studies have determined that the yield potential of a crop determines the optimum seeding rate. Jettner et al. (1999) found that the higher the yield potential of a soil, the greater the economic optimum seeding rate in a chickpea seeding rate study in Australia. Another Australian study found that the optimum plant density and yield potential of lupins depended upon the soil condition and growing season rainfall

(French et al., 1994). These studies incorporated sites from various areas, however, our study was focused on central Saskatchewan and soils and climate were very similar between sites. There was no significant site-year*treatment interaction or site-year effect for any of the crop variables measured. For this reason, we are able to determine one seeding rate for all sites, rather than a range, as suggested in several studies for various crops (French et al., 1994; Siddique et al., 1998; Jettner et al., 1999).

Grevsen (2003) similarly conducted a seeding rate study for organically produced pea and suggested that seeding rates should be higher than the recommended rate for conventional production. Grevsen (2003) found that the recommended density of 120 plants m^{-2} for organic production in Denmark was a minimum seeding rate, and that seeding rates should be as high as is economically feasible. Grevsen (2003) also stated that higher seeding rates are a long-term investment in weed management. Our study suggests a seeding rate of 200 plants m^{-2} to achieve a crop density of 120 plants m^{-2} which is similar to the results obtained by Grevsen (2003).

An optimal seeding rate for organic production of lentil was determined by Johnson (2002) in a Saskatchewan study. Johnson (2002) suggested that seeding rates should be 1.5 to 2 times higher (195 to 260 plants m^{-2}) than the recommended rate for conventional production and that increased seeding rates should be accompanied by decreased row spacing to increase the competitive ability of lentil with weeds. Our results suggest that the seeding rate of organic lentil should be similar to that determined by Johnson (2002).

5.5 Conclusions

Organic farmers should increase seeding rates of both field pea and lentil beyond the recommended rate for conventional production to increase yields and maximize profits. The economic optimum crop density for organic production of field pea in central Saskatchewan is 120 plants m^{-2}. Lentil should be seeded at as high a rate as is economically feasible for the farmer, as the return continued to increase to the highest seeding rate which yielded a crop density of 184 plants m^{-2}.

Further research to determine whether economic optimum seeding rates change with yield potential, as defined by soil type and climate within Saskatchewan, is important for organic producers in other parts of the province.

6. SUMMARY

The majority of Canadian-grown organic field pea and lentil are produced in Saskatchewan, but organic producers of these crops must rely upon recommended rates for conventional production, which may not be appropriate as production methods vary markedly between the two systems. The ultimate objective of this study was to determine optimal seeding rates of field pea and lentil for organic production in central Saskatchewan. To determine optimal seeding rates, a series of experiments were carried out in 2005 and 2006 on certified organic farms near Vonda, Vanscoy and Delisle, SK. The first experiment was performed in the field and assessed the effect of seeding rate on seed yield, weed biomass production, crop P uptake, soil N and P concentration and WUE. The second experiment studied the effect of seeding rate on AMF colonization of crop roots and was performed both in the field and as a growth chamber study. The field study investigated total percent colonization and P uptake of the two crops at three seeding rates at flowering. The growth chamber study assessed the rate of colonization of field pea roots from seedling to pod-filling and the associated P uptake by the crop. Finally, an economic analysis was conducted to determine an optimal seeding rate for organic production of field pea and lentil.

For the organic field study, a randomized complete block design was used with seeding rate of field pea or lentil as the treatment. Seeding rates were 10, 25, 62, 156 and 250 plants m^{-2} for field pea (*Pisum sativum* cv Mozart) and 15, 38, 94, 235 and 375 plants m^{-2} for lentil (*Lens culinaris* cv Sovereign). One summerfallow and one green manure treatment were included for each crop in 2005, and in 2006 an additional green manure treatment at two times the seeding rate was added to better represent actual plant densities of both green manure crops. Soil analysis at spring provided values for pH, EC, texture, soil water storage and nutrient concentrations for inorganic N and available P. Further analysis at harvest examined soil water and nutrient concentrations. Plant sampling at physiological maturity provided weed and crop biomass values.

Separation of weeds into broadleaved and grassy species provided further information on the makeup of the weed population for each seeding rate. Crop samples taken at harvest were analyzed for total available P. Statistical analyses were performed with all sites and years combined as no significant differences were discovered between sites at $P \leq 0.05$. PROC MIXED (SAS Institute Inc., 2004) was used to perform pairwise comparisons of the least squares means for each treatment. PROC NLIN (SAS Institute Inc., 2004) was used to fit curves the biomass and yield data. The equation used to describe the data was a modified version of the Michaelis-Menten model.

Seed yield increased with increasing seeding rate. For field pea, seed yield increased from 209 kg ha^{-1} at the lowest seeding rate to 1725 kg ha^{-1} at the highest rate. For lentil, seed yield increased to the highest seeding rate as well, where seed yield increased from 200 kg ha^{-1} at the lowest seeding rate to 1290 kg ha^{-1} at the highest seeding rate.

Weed biomass decreased as crop biomass increased with each successive increase in seeding rate. For field pea, the decrease in weed biomass between the rate recommended for conventional production and the optimal seeding rate for organic production was 682 kg ha^{-1} or 22%. Total weed biomass reduction between the lowest and organic recommended seeding rate was 68%. For lentil, the pattern of weed biomass decrease with increasing seeding rate was different than for field pea. Lentil is less competitive than field pea (Mishra et al., 2006), and thus may account for the differing patterns of weed biomass reduction between the two crops. The end result, however, was slightly higher but similar; the total weed biomass reduction between the recommended rate for conventional production and the optimal seeding rate for organic production was 810 kg ha^{-1} or 26%. Total weed biomass reduction between the lowest seeding rate and the organic recommended seeding rate was 59%.

Variations in soil P and total percent soil N, measured after harvest, did not show significant trends with seeding rate. There were some differences between treatments at some sites, but no consistency was found between sites for either field pea or lentil. In contrast, soil inorganic N ($NH_4^+ + NO_3^-$) was significantly affected by seeding rate. Soil from the field pea and lentil experiments had higher soil inorganic N at harvest for summerfallow and green manure treatments, as compared to the seeding rate treatments. Differences of up to 15 mg kg^{-1} (e.g., Vanscoy field pea 2006) were observed between seeding rate treatments and the green manure. For field pea, soil inorganic N increased at some sites (e.g., Delisle 2005 and Vanscoy 2006) at seeding rates of 156 and 250 plants m^{-2}, as compared to the lower seeding rates. The higher soil N levels at the high seeding rates were comparable to those with summerfallow and green manure treatments. For lentil, however, this trend was not observed and at all seeding rates, inorganic N levels were lower than for the summerfallow and green manure treatments. These results likely reflect the greater biomass produced at the higher seeding rates, and thus the greater potential for mineralization of organic N during decomposition of the crop residues.

Phosphorus concentration in the seed and straw did not change significantly with seeding rate. There was no noticeable trend with field pea. For lentil, however, P concentration did increase at higher seeding rates by approximately 200 mg kg^{-1}. The significance of these results are that for lentil, the straw residue contains more organic P at higher seeding rates, potentially leaving more P to be mineralized for the following crop.

Seed quality as determined by 100 seed weight and disease incidence did not change with seeding rate. Disease was considered to be most likely in the densest stands and therefore was tested at the highest seeding rate only. There were no disease concerns for either crop for any site. Hundred seed weight did not decrease for field pea or lentil. Harvest index, a measure of the ratio of seed to total biomass (i.e., seed+straw), decreased only at the highest seeding rate for both crops, and in both cases the change was approximately 3%. Water use efficiency increased with increasing seeding rate. The WUE measures how much seed is produced per unit of available soil moisture. Soil water was measured at spring and harvest to determine the net change in soil water storage and precipitation was added to that amount to determine soil water use. There were no significant differences between seeding rates for soil water use.

There is an advantage to seeding both field pea and lentil higher than the recommended rates for conventional production (88 and 130 plants m^{-2}, respectively). For both crops, weed biomass was reduced further and yield increases occurred beyond the recommended rates. There was no negative impact on seed quality, but a slight decrease in harvest index did occur at the highest seeding rates for both crops, indicating that a higher proportion of the plant was straw as opposed to seed at the highest densities.

Many organic producers use green manure or summerfallow to increase soil fertility and soil water storage. We grew lentil and field pea as green manure to compare the effects on soil fertility and water storage. Soil water storage and soil P were not affected by treatment, however, soil inorganic N was generally lower where the crops were grown as grain legumes as compared to green manure or summerfallow. Lentil and field pea grown as grain legumes may not be appropriate where organic growers are concerned about soil N levels for the following crop. There was a trend in pea toward increased inorganic N at high seeding rates (250 plants m^{-2}), however, growers are unlikely to plant field pea at this rate, as profitability decreased beyond approximately 175 plants m^{-2}.

Soil inorganic N may increase during the fall and spring as residues are decomposed and soil N available to the crop may be very different in spring than when measured in fall. Further research measuring the spring inorganic N values would be useful to determine the real consequence to soil inorganic N from seeding grain legumes as opposed to green manure or summerfallow. A further reason for choosing green manure or summerfallow instead of growing a grain legume crop is for the reduction in weed densities. Again, the effect of green manure and summerfallow as opposed to grain legumes on the weed population in the following crop could not be measured and would provide important information for organic growers.

In terms of profitability, organic farmers must be willing to forego any income when green manure or summerfallow are used to increase soil N or decrease weed densities. Farmers could expect a potential return of $28,080 per quarter section (160 ac or 65 ha) for field pea or $70,980 per quarter section (160 ac or 65 ha) for lentil when considering variable cost (i.e., seed cost) only.

The impact on seeding rate on AMF colonization also was examined in both field and growth chamber experiments. In the field, AMF colonization of field pea did not differ significantly between 10, 62 and 250 plants m^{-2}. Lentil, however, exhibited increased AMF colonization as seeding rate increased. Lentil straw and seed P concentration were also slightly higher at the highest seeding rates. These results are consistent with the notion that increased AMF colonization increases P uptake, as AMF colonization was also higher at the highest seeding rate than at any other.

The trend toward increased AMF colonization at high seeding rates also occurred in the growth chamber experiment with field pea. These results contradicted the majority of the literature published on crop density and AMF colonization, where decreased AMF colonization with increased density frequently has been found. All colonization levels were high (70 to 80%), however, and AMF colonization was not a concern for any seeding rate.

The rate of AMF colonization in the growth chamber experiment was not different between seeding rates at the first three harvests 10, 20 and 30 DAE. At 30 DAE, however, the lowest density treatment remained steady at 60% colonization, while the higher two densities continued to increase in percent AMF colonization up to 80% by the fifth harvest 50 DAE. The reduced availability of soil P with more intraspecific competition at the higher densities may have increased the colonization levels after 30 DAE.

AMF colonization was not significantly correlated to P in the crop, however, as previously mentioned; P concentration did increase at high seeding rates for lentil. In the growth chamber, however, P concentration was higher for the lowest seeding rate though AMF colonization was the lowest for that rate. The middle and high seeding rates in the growth chamber did not have significantly different P concentrations. Phosphorus was likely more limiting in the growth chamber than the field, as the pots used contain a limited amount of soil, and no additional P was added. Though the P concentration was lower for the middle and high seeding rates, total P uptake per pot was much higher for these rates than for the lowest seeding rate.

The high rate of AMF colonization is a positive finding for organic farmers. Phosphorus levels in organically-managed soils are often low (Knight and Shirtliffe, 2003), and root colonization by AMF has been shown to increase the uptake of P from the soil (Francis and Read, 1997). Fortunately, for the organic farms used in this study, AMF colonization was high for all seeding rates and for both crops, indicating that AMF are actively colonizing plant roots and aiding in P uptake.

For the final study, harvest data from the field experiment was used to determine potential returns for organic producers when growing field pea and lentil. Return was calculated by subtracting the variable cost (seed) from the total selling price of the grain. For statistical analysis, sites and years were combined, as there was no significant site-year*treatment interaction. PROC NLIN (SAS Institute Inc., 2004) was used to fit curves to the return data to determine where the maximum return occurred for each crop. A hyperbolic curve adapted from the Michaelis-Menten kinetics model was fitted to the lentil and a parabolic curve was fitted to the field pea data.

Returns increased to a seeding rate of 200 plants m^{-2} for field pea and then decreased at the highest seeding rate. For lentil, however, returns increased to the highest seeding rate, although the difference between 235 and 375 plants m^{-2} (\$28 ha^{-1}) was not great. The lentil return data did not reach a maximum value for the plant densities achieved in this experiment. Based on return, the economic optimum seeding rate for organic field pea is approximately 200 plants m^{-2}, while lentil should be seeded as high as economically feasible based on seed cost, as returns increased with increasing seeding rate up to 375 plants m^{-2}. When compared to the recommended rate for conventional production (88 plants m^{-2} for field pea and 130 plants m^{-2} for lentil), returns increased by \$75 and \$200 ha^{-1}, respectively (based on an organic lentil seeding rate of 375 plants m^{-2}).

Organic production systems are operated in a holistic manner, meaning that the implications of changing one aspect of production must be assessed for the entire system. Increasing seeding rates of field pea and lentil to 200 and 375 seeds m^{-2} to achieve crop densities of 120 and 184 plants m^{-2}, respectively, does indeed affect many other parts of the system. Fortunately, there were few negative implications. In fact, conditions improved as seeding rate increased for most variables measured.

Organic farmers can benefit from increasing seeding rates in a number of ways. Profitability is greatly improved beyond the recommended rate for conventional production. Weed biomass was reduced by 22% for field pea and 26% for lentil between the conventional and organic seeding rates. A reduction in weed biomass is likely associated with a reduction in weed seed production, thereby reducing the amount of seeds in the weed seed bank. This may have positive long-term implications for organic production, as weeds are one of the major constraints to crop production.

Arbuscular mycorrhizal fungi play an important role in organic farming systems and the high level of colonization for both crops at all seeding rates is encouraging. Studies have shown that P becomes more limiting over time in organic crop production systems (Gosling and Shepherd, 2005); therefore AMF colonization to increase P acquisition by crops will become more important over time. The ability of AMF to respond to very low soil P levels was demonstrated in the growth chamber experiment, where, at the highest crop density, AMF colonization was higher. This capacity of AMF to colonize crops at very high levels where soil P is deficient will be important for organic farmers in Saskatchewan where P may become more limiting over time. Seeding rate had a positive effect on AMF colonization in lentil in the field, and increasing seeding rates may be one way to ensure higher numbers of AMF for following crops.

Based on this analysis, organic producers should increase seeding rates of field pea and lentil beyond the recommended rates for conventional production to the economic optimum rates of 200 plants m^{-2} for field pea and 375 plants m^{-2} for lentil. The sole benefit an organic producer might realize in increasing seeding rates above the economic optimum rate for field pea would be additional weed suppression in the crop.

Further research investigating the proportion of N uptake occurring through N_2 fixation for each crop at varying seeding rates would be helpful to elucidate why soil inorganic N levels change with seeding rate. A soil test in spring following field pea and lentil treatments would also be a better indicator of available soil N for plant growth, as crop and weed residues would be broken down and might provide more inorganic N than indicated by the soil test at harvest. A following crop at one particular density seeded across all treatments would offer a means to study how weed seed production was affected by seeding rates of field pea and lentil, as well as how the effect of changing soil inorganic N concentrations for the various treatments affects the next crop sown.

In terms of the scope of this study, further research to determine whether economic optimum seeding rates change with yield potential, as defined by soil type and climate within Saskatchewan would be useful for organic producers in other parts of the province. Additionally, a comparison of varieties of field pea and lentil may warrant investigation, as yield and competitive differences between varieties has been noted in other studies (Shirtliffe and Johnston, 2002; Grevsen, 2003; Gahoonia et al. 2005).

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8. APPENDIX

Appendix A: ANOVA tables for data combined for sites in central Saskatchewan in 2005 and 2006

Table A.1 Analysis of variance for crop biomass, weed biomass and proportion of broadleaved weeds as affected by seeding rate of organically grown field pea and lentil in 2005 and 2006 in central Saskatchewan.

Source	df	Emergence	Crop biomass	Weed biomass	Weed number	Broadleaf weeds
		(%)	(kg ha^{-1})	(kg ha^{-1})	(weeds m^{-2})	(%)
				Field pea		
Seeding rate (SR)	5	***†	***	***	NS	*
Site-year (SY)	4	NS‡	NS	NS	NS	NS
SY*SR	20	NS	NS	NS	NS	NS
				Lentil		
Seeding rate (SR)	5	*	***	***	NS	NS
Site-year (SY)	4	NS	NS	NS	NS	NS
SY*R	20	NS	NS	NS	NS	NS

†*, **, *** significant at the 0.05, 0.01 and 0.001 probability levels, respectively

‡Not significant at $P \leq 0.05$

Table A.2 Analysis of variance for crop biomass, weed biomass, proportion of broadleaved weeds, grain yield, harvest index and 100 seed weights as affected by seeding rate of organically grown field pea and lentil in 2005 and 2006 in central Saskatchewan.

Source	df	Yield- hand harvest (kg ha^{-1})	Yield- mech. harvest (kg ha^{-1})	HI	WUE (kg ha^{-1} mm^{-1})	100 seed wt (g 100 $seeds^{-1}$)
			Field pea			
Seeding rate (SR)	5	***†	***	*	***	***
Site-year (SY)	4	NS‡	NS	NS	NS	NS
SY*SR	20	NS	NS	NS	NS	NS
			Lentil			
Seeding rate (SR)	5	***	**	*	*	***
Site-year (SY)	4	NS	NS	NS	NS	NS
SY*SR	20	NS	NS	NS	NS	NS

†*, **, *** significant at the 0.05, 0.01 and 0.001 probability levels, respectively
‡Not significant at $P \leq 0.05$

Table A.3 Analysis of variance for P concentration in seed and straw, ratio of seed P:straw P, seed and straw P uptake and AMF colonization as affected by seeding rate of organically grown field pea and lentil in 2005 and 2006 in central Saskatchewan.

Source	df	Seed P conc. (mg kg^{-1})	Straw P conc. (mg kg^{-1})	Seed P:Straw P	Seed P uptake (kg ha^{-1})	Straw P uptake (kg ha^{-1})	AMF (%)
				Field pea			
Seeding rate (SR)	5	*†	*	NS‡	***	***	NS
Site-year (SY)	4	NS	NS	NS	NS	NS	NS
SY*SR	20	NS	NS	NS	NS	NS	NS
				Lentil			
Seeding rate (SR)	5	**	***	**	***	***	***
Site-year (SY)	4	NS	NS	NS	NS	NS	NS
SY*SR	20	NS	NS	NS	NS	NS	NS

†*, **, *** significant at the 0.05, 0.01 and 0.001 probability levels, respectively

‡Not significant at $P \leq 0.05$