Field Pea and Lentil for Upper Midwest Organic Systems

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Dedication

This thesis is dedicated to my farmer mentors, Atina and Martin Diffley and Chris and Paul Burkhouse, who patiently initiated a young language geek into the world of organic agriculture.

Abstract

Two field experiments using organic methods were conducted at Rosemount, Becker, and Lamberton, MN in 2009 and 2010. The first experiment investigated the effect of intercropping on field pea (*Pisum sativum* L.) and lentil (*Lens culinaris* Medik.) yields. Intercrop treatments used were wheat (*Triticum aestivum* L.), oat (*Avena sativa* L.), oilseed radish (*Raphanus sativus* L.), winter rye (*Secale cereale* L.), rapid-cycling brassica (*Brassica campestris* L.), and unweeded and hand-weeded sole crop controls. Grain was harvested from wheat, oat, and oilseed radish, while winter rye and rapid-cycling brassica served as unharvested “living mulch” crops. Lentil and pea yields in all intercrop treatments were lower than or equal to both weeded and unweeded sole crop controls at all locations and years. Pea and lentil yields of sole crop controls equaled or exceeded total (legume plus intercrop) yields of all intercrop treatments in nearly all cases. In pea and lentil, winter rye and rapid-cycling brassica intercropping decreased weed biomass compared to the unweeded control in some treatments; however, this reduction in weed biomass did not result in improved pea or lentil yields. The second experiment investigated the effects of variety selection, delayed sowing, and weed removal on yield and weediness of spring-planted field peas and lentils. Treatments in this experiment were two lentil varieties (Crimson and Pennell) and four yellow field pea varieties (DS Admiral, Commander, Yellow, and Miami), complete manual weed removal or no weed control, and three planting dates between April 14 and May 15. Yield differences among cultivars were observed in lentils but not in peas. Yields of Crimson lentil were 66% higher on average than those of Pennell lentil. Weed removal improved pea yields by an average of 63% and lentil yields by an average of 87%, although interactions with location occurred. Average yields of peas planted at the early date were 23% and 71% greater than yields at the middle and late dates, respectively. In lentils, average yields at the early date were 50% and 120% greater than those at the middle and late dates, respectively. Delayed planting was ineffective in reducing weed biomass. Field pea reliably produced yields sufficient to offset estimated production costs in both low-price commodity and high-price direct marketing scenarios. Lentil yields did not consistently exceed economic break-even levels in most environments.

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Introduction

In organic farming systems, which are required to use biological strategies rather than synthetic chemicals, crop diversity is emphasized as an important tool in managing fertility, weeds, pests, and disease (Moncada and Sheaffer 2010). Diverse rotations build soil quality and combat disease, weed, and pest problems (Smith et al. 2008, Liebman and Davis 2000, Teasdale et al. 2004).

Nitrogen-fixing legumes are an especially important component of crop diversity in organic systems, which must use biological means of managing soil health and fertility and therefore often depend heavily on green manures and leguminous cover crops (Kuepper and Gegner 2004; Sullivan 2003). For organic farmers who do not have ready access to large quantities of livestock manure, legume-associated fixation of atmospheric N by symbiotic *Rhizobium* bacteria is the primary source of N fertility.

Lentil (*Lens culinaris* Medik.) and field pea (*Pisum sativum* L.), grain legumes suitable for a range of rain-fed and semi-arid growing conditions (McKay et al. 2003, Muehlbauer et al. 2002), are two candidates for diversification of organic rotations in the Upper Midwest. Field peas are a familiar food to US consumers, mostly in the form of hulled split peas for soup. However, currently the majority of US dry pea production is used as livestock feed, with only a small proportion sold as food (Kandel 2007). Field pea is generally classified into green and yellow cotyledon types. Yellow field peas have the advantages of being higher yielding than green varieties as well as less prone to pre-harvest seed bleaching (Kandel 2007). Oat (*Avena sativa* L.) and barley (*Hordeum vulgarum*) have been traditionally used in intercrop with pea in North American systems, and these combinations are still sold as seed mixes for forage plantings.

Lentil, a nutritious, high protein food legume originating in West Asia, has become an important crop in dryland agriculture in the Northern Great Plains region. It is a short-stature, low-biomass plant that is valued for its ability to produce a crop without seriously depleting the moisture and nutrient resources of the soil (Miller et al. 2002). The bulk of global lentil production is centered in Turkey; the Indian subcontinent; and North America, especially Canada's Prairie Provinces (McNeil et al. 2007). US-grown lentil is mostly exported despite marketing efforts to expand domestic consumption (Muehlbauer et al. 2009). However, it is increasingly used in the United States, particularly by vegetarians (Haddad and Tanzman 2003). Lentils are commonly classified into small red, large green (also called brown or yellow), and specialty market types. Red lentils are dominant in Asian markets, and are generally sold in hulled and split form. Green lentils are sold as whole seeds. Specialty types of regional importance include small mottled French green lentils such as Du Puy, small brown Spanish Pardina lentils, and black-seeded lentils (Muehlbauer et al. 2009).

At present, production of lentil and field pea in the US is heavily concentrated in the semi-arid Northern Tier states of Washington, Idaho, Montana, and North Dakota (USDA-NASS 2007). Robinson (1975) identified lentil as a crop with commercial potential for Minnesota, but no research into cultural practices for lentils has been conducted in the state since the publication of his report, and the 2007 Census of Agriculture in Minnesota listed only one farm growing lentils (USDA-NASS 2007). Although green peas are a familiar crop in Minnesota, it is only in recent decades that cultivation of conventional dry field peas has begun to expand in the state (McKay et al. 2003). The current range of edible dry pea cultivation extends somewhat further east than that of lentil, with 3303 hectares in Minnesota and 262 in Wisconsin as of 2007; however, this is only a small fraction of national production (USDA-NASS 2007).

To expand their range eastward out of the semi-arid regions, these crops will need to prove not only agronomically feasible, but also sufficiently economically productive to compete with the wider range of established crops in less water-limited environments. Minnesota, immediately to the east of North Dakota, presents a range of intermediate conditions between the water-scarce environments of the western states and the higher-rainfall environments of the Great Lakes regions. In this project we investigated the performance of field pea and lentil under organic management practices in three Minnesota environments.

For several reasons, field pea and lentil may be of particular interest to organic growers in the Upper Midwest. Well-inoculated lentils and peas are capable of fixing most of the N needed for their growth (Yadav et al. 2009; Stevenson et al. 1995). Both are generally considered to make a positive net contribution to soil N following legume grain harvest (McNeil and Materne 2007, Biederbeck et al. 1996). Additionally, these crops have short growing seasons. Early-planted lentils can reach maturity within about 85 days of emergence (Sell and Aakre 1993); typical time to maturity is 95-100 days from sowing for field peas (Kandel 2007). In the short growing seasons of the Upper Midwest, this early maturity allows for establishment of a cover crop or other fall-planted crop following legume harvest. Depending on conditions, lentil and pea residues can also decompose readily, yielding their nutrients quickly for the next crop (Veseth 1989; Lupwayi and Soon 2009).

Weeds are anticipated to be a serious constraint on the use of field pea and lentil in organic rotations. Surveys of organic farmers (Moynihan 2010; Walz 1999) show that weeds are the most commonly cited production challenge. Semi-leafless field pea cultivars are less competitive with weeds than leafy forage peas (Spies et al. 2011), and lentils are extremely susceptible to weed competition, with reductions in yield of up to 80% under weedy conditions (Al-Thahabi et al. 1994). Organic weed management tends to rely heavily on mechanical methods, but peas and lentils during and after emergence are easily damaged by cultivation (Frick and Johnson 2002; Yenish et al 2009). To minimize the need for mechanical weed removal during the season, organic growers sometimes delay seeding to allow the use of a stale seedbed technique for weed control

(Rasmussen 2003; Lamour and Lotz 2007). The short growing period of peas and lentils suggests that planting may be delayed while still allowing sufficient time for the crop to come to maturity. The standard recommendation for field pea in the Upper Midwest (Kandel 2007, Oelke et al. 1991), and for lentil in North Dakota and Canada (Saskatchewan Pulse Growers 2000, McMillan et al. 2001), is to plant as early as possible. However, early planting also exposes the crop to potentially increased weed and disease pressure (Materne and Siddique 2009), and organic production does not allow for use of antifungal seed treatments designed to protect against the diseases that can attack seedlings under cool, wet early spring conditions.

One potential way of incorporating pea and lentil into Upper Midwestern crop rotations is through intercropping, in which two or more crops are grown simultaneously in the same field. Legumes are particularly useful in intercropping systems because they do not need to compete with non-leguminous crops for soil N. The presence of a non-N-fixing intercrop can also increase fixation in the legume (Andersen et al. 2005). In the Midwest, intercropping is used primarily in forage systems, where grasses and legumes are frequently mixed to provide both high productivity and high protein content; however, intercropping can also involve two or more grain crops, or a grain crop interplanted with an unharvested companion, or "living mulch" crop, which may benefit the main crop through physical or allelopathic weed suppression and soil protection (Ateh and Doll 1996, Liedgens et al. 2004). Intercrop systems are sometimes capable of producing higher total yields than sole crops. This is often expressed in terms of a Land Equivalent Ratio (LER), which is calculated from yields of intercrop components when planted together and as sole crops; values greater than 1 indicate greater productivity per land area in intercrops than in sole crops (Mead and Willey 1980). Previous research in the Upper Midwest has observed or projected LERs both greater and less than 1, depending on crop mixture, planting pattern, cultural practices, and field conditions, in canola-soybean (Ayisi et al. 1996), mustard-sunflower (Putnam and Allan 1992) and corn-soybean (Crookston and Hill 1979) intercrops.

Several mechanisms can contribute to this yield advantage, including pest or disease control, resource use efficiency, and improved weed suppression. The success of all of these mechanisms for intercrop yield advantage is highly dependent on the specific crops used and the local growing environment (Fukai and Trenbath 1993). Intercropping may contribute to pest or disease control by changing the quality of the host plant, affecting host plant density, harboring natural enemies of pests, or affecting the ability of pests or disease inoculum to find or move among hosts (Trenbath 1993). Resource use efficiency of the intercrop exceeds that of the sole crops when intercrop components partition resources such as water, nutrients, and light through differential timing of resource demand or contrasting herbage and root structures, enabling exploration of a larger soil area or fuller light capture than either crop alone (Pridham et al. 2008; Morris and Garrity 1993). Weed growth may be suppressed when quicker canopy closure and more efficient resource capture in the intercrop deprive weeds of water, nutrients, and/or light; allelopathic properties of one intercrop component may also contribute to a reduction in weed pressure on all components (Liebman and Dyck 1993).

Both field pea and lentil have traditionally been used in intercropping systems.

Lentil culture in Asia frequently incorporates intercrops including wheat, mustard, flax, and sugarcane (Sekhon et al. 2007), while lentils in North America are generally grown as a sole crop, as intercropping is considered risky (Saskatchewan Pulse Growers 2000) and is not a familiar practice to US and Canadian growers. In current North American lentil-growing regions, lentil yield is frequently limited by available moisture. However, in the less water-limited environments east of the Dakotas, where rainfall levels are sufficient to support a more water-demanding crop, we speculated that a companion crop with strong early growth and evapotranspiration may help protect the lentil seedlings from waterlogging or poor seed set due to excess moisture (Saskatchewan Pulse Growers 2000). Based on previous research, including studies in Minnesota and North Dakota, Carr et al. (1995) suggested that both field pea and lentil intercropping may be more successful in less arid areas.

Field pea and lentil are also of interest for organic systems for marketing reasons. Many organic farmers are already marketing their products directly to consumers (Dimitri and Oberholzer 2009). Small-scale direct marketing through farmers' markets or community-supported agriculture (CSA), which offers personal connections between farmers and consumers, may allow growers to tap into the existing subset of US consumers who are already eating pulses, as well as introducing new consumers to these products. Organic consumers cite health and environmental concerns as reasons for choosing organic foods (Hughner et al. 2007). The high nutritional value of dry peas and lentils (Mitchell 2009), as well as the low environmental impact of vegetable proteins compared to meat (Pimentel 1997), suggest that organic consumers are a demographic likely to be especially receptive to these foods. Because they are storable, these crops also offer the opportunity for marketing-season extension, as well as for growers to diversify and distinguish their overall product offerings.

At present, organic markets for these crops are still small. In 2008, 6874 hectares of dry peas and lentils nationwide were certified organic, about 3% of the total crop area (USDA-ERS 2010*a*). However, an expansion of the production area of these crops and the development of suitable intercropping systems would help to broaden the available legume options and cropping methods for Upper Midwest environments, enabling organic growers to increase the profitability and long-term viability of their farms through diversification.

This project used two experiments to evaluate management practices for production of field pea and lentil in Minnesota environments. The objectives of the first experiment, discussed in Chapter 1, were to compare yields among field pea and lentil cultivars, determine the effect of seeding date on yield and weed infestation, and assess the impact of weed removal on yield of these crops. The objective of the second experiment, discussed in Chapter 2, was to determine the effect of intercrops on yield and weediness of field pea and lentil.

Chapter 1: Yield and Weed Abundance in Early- and Late-Sown Field Pea and Lentil

METHODS & MATERIALS

Field Experiment

This experiment was established at the Southwest Research and Outreach Center at Lamberton, MN, the Sand Plains Research Farm, Becker, MN, and the Minnesota Agricultural Experiment Station at Rosemount, MN. Soil at Lamberton is a Normania-Ves complex loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls); soil at Becker is a Hubbard loamy sand (sandy, mixed, frigid Entic Hapludolls); and soil at Rosemount is a Waukegan silt loam (fine-silty over sandy, mixed Typic Hapludoll). In both years of the experiment, the preceding crop was rye at Becker, soybean at Lamberton and corn at Rosemount. Soil tests in spring 2009 showed respective P, K, and

S values to be 41, 77, and 2 ppm at Becker; 46, 160, and 4 ppm at Lamberton; and 9, 159, and 4 ppm at Rosemount. Soil pH was 6.9 at Becker, 6.1 at Lamberton, and 6.7 at Rosemount. The study area at Lamberton was certified organic; those at Rosemount and Becker were not certified organic but were managed with organic practices during this study.

Average temperature during the period of 1 May to 10 July was 62° F at Becker and Lamberton and 65° F at Rosemount in 2009, and in 2010 was 63° at Becker, 64° at Lamberton, and 67° at Rosemount. Total rainfall during this period in 2009 was 12.3 cm, 16.0 cm, and 13.3 cm and in 2010 was 33.4 cm, 22.8 cm, and 34.5 cm at Becker, Lamberton, and Rosemount, respectively. At Becker, overhead irrigation was used. Total irrigation applied was 3.56 cm in 2009 and 1.52 cm in 2010.

The experimental design was a randomized complete block with split-split plots. Whole plot treatments were three planting dates, subplots were weeding treatments (hand-weeding and no weed removal), and sub-subplots were legume varieties. There were three replicates. Sub-subplots at Becker were 1.2 x 1.5 m (2009) and 1.8 x 2.4 m (2010), at Rosemount 1.2 x 2.4 m (2009) and 1.8 x 2.4 m (2010) and at Lamberton 1.5 x 6.1 m (2009) and 1.5 x 3.7 m (2010). Plot size was changed between years owing to differences in the dimensions of available field space. Seeding rates, based upon commercial recommendations, were 108 live seed m^{-2} for peas and 151 live seed m^{-2} for lentils (McKay et al. 2003; Saskatchewan Pulse Growers 2000; McMillan 2001). The entire field was tilled before planting the first date, and blocks for subsequent dates were re-tilled immediately before planting to kill germinated weed seedlings, with the sole exception of the second date at Becker in 2009, where no weed germination was observed before planting. Seed was planted in 20.3 cm rows at a depth of 7.6 cm. The early plantings took place between 17-24 April 2009 and 14-20 April 2010. Middle plantings were between 29 April-5 May 2009 and 23-29 April 2010. Late plantings were between 11-15 May 2009 and 5-10 May 2010.

Pea varieties in 2009 were DS Admiral, Miami, and a variety not specified organic line (Albert Lea Seed House, Albert Lea, MN), and in 2010 were DS Admiral and Commander. All pea varieties were semi-leafless with medium-sized yellow-cotyledoned seed. DS Admiral is an early-maturing variety with medium vine length. Miami is a medium-maturity variety, also with medium vine length. Commander has been observed to have similar vine length and maturity to DS Admiral (NDSU 2009). We selected these varieties based on seed availability, and because they were in common use in the region.

Lentil varieties planted in both years were Crimson and Pennell, both of which are standard varieties in North American lentil cultivation (Muehlbauer et al. 2009). Crimson is a small-seeded red lentil with good drought tolerance, erect growth habit, and medium-sized leaflets (Muehlbauer 1991). Pennell is a large-seeded brown lentil with yellow cotyledons and an upright, bushy growth habit (Muehlbauer and McPhee 2004). In 2009, two newer large brown varieties, Riveland and Richlea, were also included. Planting of Riveland and Richlea was not repeated in 2010 due to space and labor constraints; however, an unspecified small-seeded speckled French green variety was included in 2010. To avoid confounding of variety and year, our analysis includes data from Crimson and Pennell lentil only; yields of all varieties are shown in Appendix A.

Weeding treatments were no weed control and complete weed removal. Hand-weeding of weeded treatments was conducted approximately every 1 to 3 weeks as needed to maintain a weed-free environment. Weeding was discontinued in pea plots when pea canopies closed, about eight weeks after planting, at which point it was no longer possible to enter the plot without damaging the peas. Weed population counts were taken approximately 4-5 weeks after planting.

PyGanic organic-approved (Organic Materials Review Institute 2011) insecticide (pyrethrins), mixed according to package directions, was applied to lentils at Rosemount and Becker locations in June 2010 following observation of leafhoppers.

A 1.0 m^2 quadrat was harvested by hand from each plot at legume maturity. Harvest took place in 2009 between 15 July and 3 August, and in 2010 between 15 July and 10 August. Weeds were separated from legumes. Peas, lentils, and weeds were dried at 60 C for at least 48 hours before weighing. Legumes were threshed using a roller thresher, and seed was separated from straw and chaff using a seed cleaner. Grain and biomass yields in this analysis are expressed on a dry matter basis.

Data were analyzed as split-split plots in mixed models using proc mixed in SAS software (Version 9.2, SAS Institute Inc, Cary, NC). Grain yield data were log-transformed to correct non-normality. Treatment contrasts were made using Tukey-Kramer adjusted least square means comparisons. To avoid confounding of lentil variety with year, only Crimson and Pennell varieties were included in our statistical analysis of lentil. Treatment effects were declared significant at $P > 0.05$.

Economic Analysis

We estimated costs for organic field pea and lentil production based upon equipment and labor costs as calculated by Lazarus (2011). Seed costs are based on the rates used in this experiment, derived from commercial seed rate recommendations. Pea seed cost uses 2011 price of certified organic DS Admiral pea seed (Albert Lea Seed House, Albert Lea, MN). Lentil seed cost is based on 2011 prices (Pulse USA, personal communication, 2011). Because we were unsuccessful in efforts to locate a consistent source of organic lentil seed, we have based lentil seed price on the cost of untreated nonorganic seed, as permitted by NOP Rule §205.204. Relative prices of green and red lentil have fluctuated in recent years. Our calculations use prices and seed rates for conventional (non-herbicide-tolerant) green lentil.

Revenues were calculated for two price scenarios: a high-price scenario, in which organic peas and lentils are sold directly to consumers, providing the grower with the full retail value of the crops; and a low-price scenario, in which organic peas and lentils are sold post-harvest on available markets, and some premiums are lost. Because buyers may not be available for organic lentil or organic food-grade dry pea, this scenario assumes that lentils are sold as conventional, while peas are sold as organic feed-grade. Prices used are as of summer 2011 (USDA-ERS 2011, Inman 2011). Following previous research (Pirog and McCann 2009, Kaemingk 2010, Claro 2011) indicating that farmer's market prices for organic products may be lower or higher than retail, depending on the item type, season, and quantity purchased, we have set pea and lentil prices in the high-price scenario equal to retail prices, which were taken from bulk prices of organic lentil at Twin Cities natural food co-operatives in August 2011. We used estimated production expenses and prices of lentil and pea to calculate a break-even yield for each crop in each scenario; this is the yield level at which the value of the crop produced is equal to the cost of production.

RESULTS AND DISCUSSION

Pea

When pea yields from all environments (defined as location by year combinations) in the experiment were analyzed together (not shown), the effects of planting date and weeding treatment on pea grain yield were inconsistent over locations and years, resulting in a highly significant ($P = 0.0001$) three-way interaction of planting date by weeding treatment by environment. Due to this interaction, we analyzed the results from each location separately (Table 1). Because no major phenotypic differences between varieties were observed, and main and interaction effects of pea variety were non-significant ($P > 0.05$) at all locations, results for all varieties were pooled in these analyses.

Although treatments effects differed among locations, there was a clear location effect on pea yield. Average pea yields (Table 2) were 29% and 39% higher at Becker and Lamberton, respectively, than at Rosemount. Pea is a crop adapted to semi-arid climates (McKay *et al*. 2003) and was quite tolerant of the very sandy soil at Becker, as seen from the fact that yields did not differ between Becker and Lamberton during the dry 2009 growing season. Pea is also a cool-season crop (Kandel 2007), and slightly higher temperatures at Rosemount may have contributed to reduced yields at that location.

The three-way interaction of planting date by weeding by year at Rosemount and Lamberton is attributable to late, incomplete and somewhat inconsistent removal of weeds from hand-weeded plots in 2009 due to time and labor constraints, a problem that was mostly remedied in 2010. Dominant weeds at Rosemount and Lamberton were green foxtail (*Setaria viridis*), redroot pigweed (*Amaranthus retroflexus*), and lamb's-quarters (*Chenopodium album*); dominant weeds at Becker were wild buckwheat (*Polygonum convolvulus*), green foxtail, and purslane (*Portulaca oleracea*).

Pea yields are known to be sensitive to weed competition (Harker et al. 2001), and our results confirm this. Weed biomass in the plots (Fig. 1) was inversely correlated with pea yield ($R^2 = 0.3307$, $P < 0.0001$). As we expected, weed removal increased yields at all sites, although the magnitude of the effect varied. Yields in weeded plots were higher than those of unweeded plots by 21% at Becker, 53% at Lamberton, and 173% at Rosemount. The smaller weeding effect at Becker can be attributed to the very low weed populations and biomass compared to Rosemount and Lamberton, where unweeded plots were often heavily infested with weeds (Table 3). These yield benefits from weeding are similar to, but more variable than, those observed by Harker et al. (2001).

Despite the planting date by environment interaction, a clear pattern could be seen of higher yields at earlier planting dates. Across locations, years, and weeding treatments, yields of early plantings exceeded those of middle and late plantings by 23% and 71%, respectively. Weed biomass increased with delay in planting date (P = 0.0086), indicating that decreased weed pressure was one advantage to early planting. However, when only weeded plots were considered, average yields across environments were lower in the middle date than the early date (P = 0.471) and lower in the late date than the middle date (P = 0.0053). Yield of weeded plots in the late date did not exceed yield of unweeded plots in the early date. This indicates that factors other than weed pressure were associated with later-season planting and also negatively impacted yield, likely including excessive heat at flowering time, as indicated by Kandel (2007).

The use of re-tillage in our delayed (middle and late) planting treatments did not result in reduced weed biomass. Recommendations for stale seedbed (Lamour and Lotz 2007) call for extremely shallow disturbance in the pre-planting pass in order to avoid bringing new weed seed to the soil surface. This experiment used a rototiller, which would have drawn a considerable quantity of new weed seed to the surface. However, a true stale seedbed would also have been unlikely to be effective at these sites, where soil weed seedbanks are extremely well-stocked. Weed seedling counts of up to 990 m^{-2} were observed at Rosemount, and up to 2282 m^{-2} at Lamberton. Weed seedling counts at Becker, although much lower on average, also ranged up to 807 per m^{-2}. At such high population densities, soil and moisture conditions and competition among weeds, not number of germinating seedlings, were likely the determining factors in weed biomass. The quantity of weeds killed by the second tillage pass would probably have been simply insufficient to bring seedling populations below the threshold where biomass would have been limited by population.

Lentil

As with peas, we analyzed lentil grain yields separately by location (Table 4) because of significant interactions of environment by planting date and weeding treatment.

Average Crimson and Pennell lentil yields (Table 5) were decidedly higher at Becker than at Lamberton and Rosemount in both 2009 and 2010 (P < 0.0001). Pooled across treatments, lentil yields were 288% and 417 % higher at Becker than at Lamberton and Rosemount, respectively. Differences in yields between Lamberton and Rosemount were not consistent, as Rosemount yields, on average, exceeded those at Lamberton in 2009 (P = 0.0115), but Lamberton yields exceeded those at Rosemount in 2010 (P = 0.0185), possibly due to high temperatures in that year at Rosemount. The increased yields at Becker, particularly during the unusually wet 2010 season, may have been due to the sandy soil preventing waterlogging, to which lentils are known to be sensitive (McMillan 2001). We suspect that the extended vegetative period and flower abortion observed in Pennell lentil at all locations in 2010 may be symptoms of excess rainfall and/or heat during flowering (Muehlbauer et al. 2002). Rapid drainage through the sandy soil at Becker may have partially mitigated the effects of badly timed precipitation. High yields in unweeded plots at Becker can be attributed to the relatively low level of weed infestation at this location.

Crimson was, at all locations, a higher-yielding variety than Pennell. Pooled across treatments and locations, Crimson yields averaged 65% higher than those of Pennell. In the 2010 growing season, Pennell lentil showed widespread flower abortion with few pods coming to maturity. Pennell plants remained green and continued to flower after Crimson and French varieties had matured. In our plantings, Pennell showed noticeably larger leaflets than Crimson, and slightly lighter leaf color. We also observed considerable lodging in both varieties. Our results should not be interpreted to mean that red lentils are generally higher-yielding than brown lentils. Although varieties were selected to represent a range of market types, observed differences in performance among Pennell, Riveland, and Richlea lentil in this experiment (Appendix A), as well as previous research (Sultana et al. 2005), indicate that varieties can differ considerably within market type.

As shown in previous research (Erman et al. 2008; Al-Thahabi et al. 1994), lentils are highly susceptible to competition from weeds. For lentils, as for peas, weeding did not improve yields at Becker due to low levels of weed pressure. However, at other locations, where substantial weed populations were present, yields in unweeded plots were generally only a fraction of those of their weeded counterparts. Unweeded plots at both Rosemount and Lamberton were completely overtaken by weeds and produced very low lentil yields, particularly in the 2010 season, when yields in unweeded plots were near zero. Harvested material from these plots contained few or no lentil plants, and those that were present had almost no fully formed pods. We did not observe differences between varieties in their response to weeding. Although lentil varieties vary in their growth habits (Saxena 2009), McDonald et al. (2007) and Tepe et al. (2005) indicate that variety selection alone is not effective in improving the competitiveness of a lentil crop.

Despite the date by environment interaction and considerable variability in the data, it was clear that the overall trend at all environments was that earlier planting produced higher yields. The magnitude of this effect varied by date and year, but in no case were yields significantly improved by later planting. Across weeding treatments, yields in the earliest date in 2009 and 2010, respectively, were 96% and 49% higher than those in the latest date at Becker, 351% and 292% higher at Lamberton and 2358% and 678% higher at Rosemount. These results echo standard planting recommendations as well as much research indicating that delayed sowing is disadvantageous across a wide range of lentil-growing climates (Turk et al. 2003; Ali et al. 2009; Saskatchewan Pulse Growers 2000).

Weed biomass in unweeded lentil plots was inversely correlated with yield (R^2 = 0.5790, $P < 0.0001$). However, weed biomass was not affected by date of planting, indicating that delaying planting was not effective at reducing weed pressure, and that improvements in yield with earlier planting were not due to reduced competition from weeds. As with the peas, we suspect that excessive heat and moisture during flowering may have contributed to the reduction in yields of Date 3 lentil plantings.

Economic analysis

Field pea production costs (Table 6) are estimated to be \$348.88 ha^{-1}, and lentil production costs are estimated at \$398.30 ha^{-1}. Our estimates of field and lentil production costs are similar to costs of organic soybean production reported by McBride and Greene (2009). Our calculation assumes that no weed control methods are applied; however, mechanical weed control by rotary hoeing would be relatively low-cost at \$6.25 ha^{-1} (Lazarus 2011) and may be effective in some environments. Further studies would be required to determine whether reductions in weed pressure by mechanical cultivation would be sufficient to offset equipment and labor costs and damage to the crop.

Price discovery and market access can be major difficulties for organic producers (Ferguson et al. 2005). Because organic commodity prices respond to factors internal to organic markets and may not be predictable from conventional prices (Singerman et al. 2011), relying on organic price premiums may be risky for growers, and, in particular, organic lentils may be difficult to sell unless grown under contract. However, lentil and pea are well suited to direct sale to consumers through a farmer's market or similar arrangement because these crops are commonly purchased in an unprocessed or minimally processed state. In many cases, direct-market farmers are vegetable growers whose systems routinely include hand-weeding, and who may be more willing and able to successfully grow a crop that is vulnerable to weed competition.

Yields of early-planted field pea (Table 7) consistently exceeded the break-even level at all locations and in both weeded and unweeded treatments. In lentil, break-even yields for the low-price scenario were achieved only at Becker. Both weeded and unweeded treatments at Lamberton and Rosemount fell below yields required to offset production costs. However, in the high-price scenario, lentil yields exceeded the break-even level in weeded treatments at all locations and in unweeded treatments at Becker. Unweeded yields at Lamberton and Rosemount were below the break-even level. Because the calculated production costs do not include weed control, the profitability of lentil for growers facing significant weed pressure would depend on the cost, availability, and effectiveness of labor and/or equipment for mechanical weed removal.

The relative profitability of pea and lentil compared to other crops will depend on soil conditions, weed pressure, and market and input price fluctuations. However, our analysis suggests that field pea is likely to be a profitable component for Minnesota organic rotations. Lentil is not consistently profitable when marketed in a low-price commodity scenario; however, it may prove economically advantageous to farmers who are marketing directly to consumers, particularly under favorable conditions such as on sandy soils where other crops may struggle, or where weed pressure is low; or when used for a specialized purpose such as extending the market season or distinguishing the grower's product offerings from competitors'.

CONCLUSIONS

The results of this experiment indicate that both lentil and pea yields are improved by early planting, and that delayed sowing following re-tillage does not reduce weed impact on the crop. Lentil performance differed by variety, while no differences were observed among the pea varieties. Both pea and lentil yields improved with weeding.

Lentil yields were frequently near zero when high weed populations were not controlled. Pea yields, although also depressed by weed pressure, were not as severely affected as those of lentils.

Yields of early-planted field peas in this experiment, in both weeded and unweeded treatments, compared favorably to those reported under conventional management in varietal trials in Minnesota (Moncada et al. 2010) and North Dakota (Akyuz et al. 2010). Our observed lentil yields mostly fell below averages reported for Canadian (Saskatchewan Pulse Growers 2000) and North Dakota (USDA-NASS 2011) growers. Lentil may still prove to be useful to organic growers in the rain-fed Upper Midwest, but the extremely wide range of lentil yields obtained in this experiment suggests that, before the crop can be recommended to growers, considerable further study will be necessary, particularly on methods of weed control and variety performance and susceptibility to constraints such as fungal disease and insect predation under the state's unpredictable temperature and rainfall conditions.

Field pea reliably produced yields sufficient to offset estimated production costs in both low-price commodity and high-price direct marketing scenarios, even when weeds were not controlled. Lentil yields generally did not exceed the break-even level in the low-price scenario, but often did in the high-price scenario, indicating that lentil will be unprofitable except under favorable growing conditions or for specialized purposes in direct-marketing systems.

Chapter 2: Productivity of Field Pea and Lentil with Cereal and Brassica Intercrops

METHODS & MATERIALS

The experiment was established in 2009 and 2010 at the Southwest Research and Outreach Center at Lamberton, MN, the Sand Plains Research Farm, Becker, MN, and the Minnesota Agricultural Experiment Station at Rosemount, MN. Soil types were as described in Chapter 1. The preceding crop in both years of the study was rye (*Secale cereal*) at Becker, soybean (*Glycine max*) at Lamberton, and corn (*Zea mays*) at Rosemount. Soil tests in spring 2009 found respective P, K, and S values to be 41, 77, and 2 ppm at Becker; 46, 160, and 4 ppm at Lamberton; and 9, 159, and 4 ppm at Rosemount. Soil pH was 6.9 at Becker, 6.1 at Lamberton, and 6.7 at Rosemount. The Lamberton study site was certified organic; those at Rosemount and Becker were not certified organic but were managed with organic practices during this study.

The experimental design was a randomized complete block with subplots. Whole plot entries were legume varieties and subplots were intercrop treatments. Intercrop entries were spring wheat (*Triticum aestivum* L. var. RB07), oat (*Avena sativa* L. var. Souris), oilseed radish (*Raphanus sativus* L.), winter rye (*Secale cereale* L.), rapid-cycling brassica (*Brassica campestris* L.), and two no-intercrop checks, one without weed control and the other hand-weeded. RB07 and Souris are standard varieties in Minnesota small grain production. Oilseed radish is a fast-growing, deep-rooted, large-seeded mustard developed for oil production but also commonly used as a cover crop (Ngouajio and Mutch 2004). Rapid-cycling brassica is a small-stature crop with a life cycle of approximately 42 days between emergence and senescence. The line used in this experiment was selected for use as a smother crop, intended to suppress weeds early in crop growth, then die without requiring chemical or mechanical termination (K. Betts, personal communication, 2010). Grain was harvested from wheat, oats, and oilseed radish, while rapid-cycling brassica and winter rye were used to produce herbaceous growth and were not expected to yield harvestable grain.

All pea varieties were semi-leafless with medium-sized yellow-cotyledoned seed. Pea varieties in 2009 were DS Admiral and an unspecified organic yellow field pea (Albert Lea Seed House, Albert Lea, MN), and in 2010 were DS Admiral and Commander. DS Admiral is an early-maturing variety with medium vine length. Commander has been observed to have similar vine length and maturity to DS Admiral (NDSU 2009). We selected these varieties based on seed availability, and because they were in common use in the region.

Lentil varieties planted in both years were Crimson and Pennell, both of which are standard varieties in North American lentil cultivation (Muehlbauer et al. 2009). Crimson is a small-seeded red lentil with good drought tolerance, erect growth habit, and medium-sized leaflets (Muehlbauer 1991). Pennell is a large-seeded brown lentil with yellow cotyledons and an upright, bushy growth habit (Muehlbauer and McPhee 2004).

Plots were established between 17-23 April in 2009, and between 12-20 April in 2010. Legumes and intercrops were planted concurrently at each location except at Rosemount in 2010, where intercrop seeding was delayed until two days after legume seeding. Peas and lentils were drilled in 20.3 cm rows at a depth of 7.6 cm; intercrops were drilled in 20.3 cm rows in a separate pass at a depth of 3.8 cm except for rapid-cycling brassica, which was broadcast. Seeding rates, based upon commercial recommendations, were 108 live seed m^{-2} for peas and 151 live seed m^{-2} for lentils (McKay et al. 2003; Saskatchewan Pulse Growers 2000; McMillan 2001). Seeding rates for intercrops were: wheat and oat, 215 live seed m^{-2}; oilseed radish, 75 live seed m^{-2}; winter rye, 129 live seed m^{-2}; and rapid-cycling brassica, 1076 live seed m^{-2}. All seed used in this experiment was untreated. Pea seed was certified organic. All peas and lentils were inoculated with appropriate *Rhizobium* strains.

In 2009, total precipitation during the period of 15 April to 15 July was 19.2, 19.1, and 18.1 cm at Becker, Lamberton, and Rosemount, respectively. Precipitation during the same period in 2010 was 36.6, 28.4, and 37.6 cm, respectively. Supplemental overhead irrigation was also used at Becker; total irrigation applied was 3.56 cm in 2009 and 1.52 cm in 2010. During this period, respective mean temperatures at Becker, Lamberton, and Rosemount were 16° C, 16° C, and 17° C in 2009 and 17° C, 17° C, and 18° C in 2010.

Weeds were removed from weed-free treatments by hand throughout the season. Depending on rainfall and weed growth, weeding took place approximately every 1 to 3 weeks. Weeding of pea plots was discontinued following canopy closure, approximately 8 weeks after planting, at which point it was no longer possible to enter the plots without damaging the peas. PyGanic organic-approved (Organic Materials Review Institute 2011) insecticide (pyrethrins), mixed according to package directions, was applied to lentils at Rosemount and Becker locations in June 2010 following observation of leafhoppers.

1 m^2 quadrats were harvested by hand from each plot after pea and lentil reached maturity, between 16-28 July 2009 and 14 July - 5 August 2010. In most cases, legume maturity corresponded closely with maturity of intercrops. Weeds, intercrops, and legumes were separated and all harvested material was dried for 72 hours at 60° C before weighing. Peas, lentils, wheat, oats, and oilseed radish were threshed using a roller thresher and seed was mechanically cleaned, and grain yield for these crops was recorded. Biomass yields were recorded for winter rye, rapid-cycling brassica, and weeds. All weights are expressed on a dry matter basis.

Data were analyzed as split plots blocked by location using SAS proc mixed (Version 9.2, SAS Institute Inc, Cary, NC). Initial analysis used year as an additional blocking variable; however, because year was involved in multiple significant interaction effects (not shown) on legume yields, and to avoid confounding of year with pea variety, data from 2009 and 2010 were analyzed separately for both peas and lentils. Treatment contrasts were made using Tukey-Kramer adjusted least square means comparisons. Treatment effects were declared significant at $P < 0.05$.

RESULTS AND DISCUSSION

Lentils

Although interaction effects (discussed below) occurred, clear differences in lentil performance were observed among the three locations (Table 8). Lentil grain yields, averaged across treatments, were 1027% and 186% higher at Becker than at Rosemount and Lamberton, respectively, in 2009, and 929% and 939% higher 2010. Total (lentil plus intercrop) grain yields were 76% and 100% higher at Becker than at Lamberton and Rosemount in 2009, and 751% and 665% higher in 2010. Neither lentil nor total grain yields differed between Lamberton and Rosemount. Both weeded and unweeded lentils at Becker achieved yield levels (Table 9) expected in commercial lentil culture in North America (Saskatchewan Pulse Growers 2000; USDA-NASS 2011). Weeded lentils performed inconsistently at Lamberton and Rosemount, reaching commercially acceptable yields for both varieties at Lamberton in 2009 and for Crimson lentil at Rosemount in 2010. Weeding resulted in consistently higher yields than when not weeded at both Lamberton and Rosemount.

Lentil is known to be highly susceptible to weed pressure (Erman et al. 2008). As described in the previous chapter, weed populations at Lamberton and Rosemount were extremely high, while weed growth at Becker was inhibited by moisture and fertility limitations. Average weed biomass in unweeded control plots at Becker was only 23 g m^{-2}, compared to 794 g m^{-2} at Lamberton and 599 g m^{-2} at Rosemount.

Weed pressure was not the only factor in the yield advantage of lentil plantings at Becker over those at other locations. At Lamberton in 2009, in Pennell lentil at both Lamberton and Rosemount in 2010, and in Crimson lentil at Rosemount in 2010, lentil yields in hand-weeded plots were lower than at Becker. This suggests that extremely sandy and fast-draining soil conditions at the Becker location were favorable to lentil in both the drier 2009 season and the much rainier 2010 season. Lentil is known not only to have low water demand (Andrews and Mackenzie 2007), but also to be susceptible to waterlogging (McMillan 2001), which may have hindered growth in the finer-textured soils at Rosemount and Lamberton.

Because there was no interaction of variety with other effects on lentil yield or total yield in 2009, location and intercrop effects are shown pooled across varieties in that year. Average yields of Crimson lentil were 29% higher than those of Pennell in 2009, but because intercrop yields were more variable, we did not find a significant difference in average total yield with lentil variety in that year. In our plantings, Pennell showed noticeably larger leaflets than Crimson, and slightly lighter leaf color. We also observed considerable lodging in both varieties.

In 2010, Crimson yields exceeded those of Pennell by an overall average of 111%, but the magnitude of the variety effect varied by location and intercrop. At Rosemount and Lamberton, variety differences were partly obscured by the general poor performance of unweeded treatments. Widespread flower abortion was observed in Pennell, our large-seeded green lentil, in 2010, particularly at Rosemount and Lamberton. This variety continued vegetative growth into August and continued to flower, but set very little seed. Although there is much variation within types, lentils of the small red type have been found to be more drought tolerant on average than larger-seeded yellow (green/brown) lentils (Erskine 1996), and are more widely grown in regions where timing of seed maturation coincides with increasing temperatures (Materne and Siddique 2009). In this experiment, it was the small red variety that performed better in both the cool, dry conditions of 2009 and the warmer, wetter conditions of 2010. Although the varieties used cannot necessarily be assumed to be representative of their respective types, this suggests that moisture and temperature sensitivity will be important traits to consider in future evaluations of lentil varieties for Minnesota planting given the great variability in quantity and timing of summer rainfall in the state.

We found no evidence of an increase in total grain productivity resulting from intercropping of lentil with the five intercrops in this experiment. Effects of intercrop on lentil yield and total (lentil plus intercrop) yield varied by location and, in 2010, by lentil variety (Table 8). Lentil yields in the harvested intercrops were less than or equal to yields of weeded and unweeded sole crop lentil in all locations, years, and lentil varieties. Total grain yields in the three harvested intercrop treatments were also less than or equal to those of weeded and unweeded sole crop of lentil in all locations and years except for the 2009 season at Lamberton (Table 9), when low lentil yields in all treatments combined with higher yields of wheat, oat, and oilseed radish to produce higher total yields in the in harvested intercrop plots than in the lentil sole crop controls.

Previous Asian and North American studies have demonstrated that intercrops of lentil with cereals, mustards, and flax can achieve a Land Equivalent Ratio well above 1 (MacMillan et al. 2001; Schmidtke et al. 2004, Lal et al. 1998, Banik et al. 2000, Mandal and Mahapatra 1990). Because we did not find such an effect, we suspect that our study environments and lack of weed control were particularly unfavorable to successful intercropping. Yields of wheat, oat, and oilseed radish at Lamberton in 2009 were comparable to yields in monoculture reported elsewhere for these crops (Phelps et al. 2007; USDA-NASS 2010), but were lower in all other locations and years. Because we did not have a sole crop control of wheat, oat, or oilseed radish, we were unable to calculate an LER for the intercrops. However, our observations suggest that the cereals and radish, while providing sufficient competition to hinder lentil growth, produced insufficient seed yield, likely due to low-fertility and extremely fast-draining soil conditions at Becker, and severe weed pressure at Rosemount and Lamberton, to compensate for the loss of lentil productivity.

In some cases, the unharvested or “living mulch” intercrops (winter rye and rapid-cycling brassica) were successful in lowering the weed biomass in the plot compared to the unweeded control (Table 10). Weed biomasses were lower than the unweeded control in the winter rye treatment at Lamberton and Rosemount in both years, and in the rapid-cycling brassica treatment at these locations in 2010. At Lamberton in 2009 and Rosemount in 2010, total combined biomasses of intercrop and weeds were lower in the winter rye treatment than in the unweeded control. However, lentil yields in both of the living mulch treatments were less than or equal to those in the weeded and unweeded controls in all years, locations, and varieties. Ateh and Doll (1996), who studied winter rye as a living mulch in soybean, similarly found that it was capable of suppressing weeds but could also damage crop vigor.

Peas

Unlike in lentils, pea and total (pea plus intercrop) grain yield were similar among locations when averaged across weeding and intercrop treatments. However, respective pea yields in the weeded control treatment at Lamberton and Rosemount were 28% and 48% higher in 2009, and 91% and 43% higher in 2010, than those at Becker. This indicates that yield potential of peas was higher in the less droughty soil conditions at Rosemount and Lamberton, but yields in treatments that had not been hand-weeded at these locations were more adversely affected by weeds than at Becker, where weed biomass was lower for the reasons noted above. Previous research confirms that field pea yields are susceptible to weed pressure (Harker et al. 2001); however, peas suppressed weed growth noticeably more than lentils. Average weed biomasses in unweeded pea control plots were 10 g m^{-2}, 95 g m^{-2}, and 193 g m^{-2} at Becker, Lamberton, and Rosemount, respectively.

Pea varieties gave similar yields, except in 2010 at Rosemount, where average yields of Admiral were 61% higher than those of Commander due to uneven emergence of Commander. This difference was responsible for the location x variety interaction effect observed in that year. The emergence problem may have been due to differences in susceptibility to disease. DS Admiral is moderately susceptible to *Fusarium* wilt (Andersen et al. 2002), while disease susceptibility of Commander has not been published.

There were significant interaction effects of location x intercrop (Table 11) on pea yield and total yield. Depending on location and year, pea yields (Table 12) in both weeded and unweeded controls either equaled or exceeded those in all of the harvested intercrop treatments (wheat, oat, and oilseed radish). At Lamberton in 2009 and Rosemount in 2010, pea yields were lower in the oat intercrop than in the unweeded control. Wheat and oilseed radish also reduced pea yields compared to unweeded sole pea crop at Lamberton in 2009. In all other locations and years, pea yields in the harvested intercrop treatments were indistinguishable from those in the unweeded control. At Rosemount in 2009, and at Lamberton in both study years, pea yield in all three harvested intercrop treatments was also lower than in the weeded control. At Becker, intercrop treatments had no effect on either pea or total (pea plus intercrop) grain yield.

Total grain yields in all intercrop treatments were less than or equal to yields of unweeded sole crop pea at all locations and years. This means that, although it was not possible to calculate exact LER values, potential LER would be very unlikely to be greater than 1 in any of these treatments. Other studies (Mohler and Liebman 1987; Neumann et al. 2007; Ghaley et al. 2005; Szumigalski and Van Acker 2005; Andersen et al. 2005) have found relative productivity of sole and intercrops of pea with cereals and brassicas to be variable and dependent upon several factors, including planting density, N fertilization, and weed pressure. As discussed above for lentils, we suspect that the constraints imposed by soil conditions at Becker and weeds at the other locations did not allow intercrops to be sufficiently productive to compensate for their negative impact on pea yields.

In the two living mulch treatments (winter rye and rapid-cycling brassica), weed biomass was reduced by the presence of the intercrop compared to the unweeded control. Unlike in lentils, this effect in peas was consistent across locations and years. Weed biomasses in winter rye and rapid-cycling brassica treatments averaged 40% and 25% lower, respectively, than those of the unweeded control. However, total (intercrop plus weed) non-pea biomass (not shown) did not differ among the three treatments, and pea yields were not improved by the addition of the intercrops, indicating that the presence of these living mulches was no less detrimental to the pea crop than the presence of weeds.

Summary

Yields of weeded and unweeded lentils reached commercially acceptable levels, in excess of 1000 kg ha^{-1}, on sandy soils at Becker. Lentil yields at Lamberton and Rosemount were very low when unweeded, and higher but inconsistent when weeds were controlled. Yields of the Crimson lentil variety were higher than those of Pennell. Pea yields were within or above average levels for US production (USDA-ERS 2010*b*), and were higher at Lamberton and Rosemount than at Becker when weeded, but not when unweeded. Intercropping of lentil and field pea with wheat, oat, and oilseed radish did not result in greater legume yields or total grain yields than lentil and pea sole crops. Wheat, oat, and oilseed radish intercrops reduced legume yields without producing enough grain to offset this reduction. Living mulch intercrops of winter rye and rapid-cycling brassica sometimes reduced weed biomass in lentil and pea, but did not result in higher legume yields than unweeded lentil and pea sole crops, indicating that these living mulches were not an effective method of organic weed control. Because previous studies have demonstrated yield gains with intercropping of these crops, but have also shown intercrop effects to vary with environmental conditions, and especially because of the diversity of cropping systems and conditions among organic farms, we note that these results must be interpreted as specific to the three Minnesota study environments used.

Tables and Figures

Table 1. Test of fixed effects on pea grain yield by location, combined 2009-2010 data

	Becker			Lamberton			Rosemount		
Effect	**F**	**Pr >F**	**Sig.**	**F**	**Pr >F**	**Sig.**	**F**	**Pr >F**	**Sig.**
Date (A)	27.84	0.0002	**	22.07	0.0006	**	18.78	0.0010	**
Weeding (B)	6.98	0.0215	*	128.21	<.0001	**	25.4	0.0003	**
Year (C)	40.31	0.0032	**	42.83	0.0028	**	5.81	0.0736	
A*B	0.68	0.5272		14.27	0.0007	**	1.72	0.2211	
A*C	3.76	0.0705		24.43	0.0004	**	0.9	0.4427	
B*C	0.99	0.3388		72.47	<.0001	**	4.39	0.0580	
A*B*C	0.67	0.5275		16.62	0.0003	**	6.19	0.0142	**

* Significant at 0.05 level of probability

** Significant at 0.01 level of probability

Table 2. Average pea grain yields in 2009 and 2010 as affected by location, weeding treatment, and planting date

	Becker			Lamberton			Rosemount		
	2009	2010	Total	2009	2010	Total	2009	2010	Total
Date					kg ha^{-1}				
Early	4869	2511	3926a†	3698a	3443a	3596	3492	2613	3140a
Middle	3192	2392	2872b	3084a	3124a	3100	3238	2078	2774a
Late	2408	1903	2206c	3578a	2139b	3003	1371	650	1083b
Total	3490	2269	2710	3084	2591	3233	2700	1780	2082
Weeded									
No	3082	2074	2679a	3198a	1587a	2554	1544	807	1249a
Yes	3897	2464	3324b	3709b	4217b	3913	3857	2754	3416b

† All mean separations are within locations. Mean separations at Becker and Rosemount are pooled across years. Values with same letter are not significantly different (α = 0.05, Tukey-Kramer adjusted comparisons)

Table 3. Average weed biomass in unweeded pea and lentil plots in 2009 and 2010 as affected by location and planting date

	2009			2010			Total†
	Becker	Lamberton	Rosemount	Becker	Lamberton	Rosemount	
Pea				$g\ m^{-2}$			
Early	63	114	312	21	293	325	183A
Middle	114	225	499	26	525	177	265B
Late	95	229	349	28	643	414	284B
Total†	92ab	190b	390cd	25a	487d	305c	
Lentil							
Early	37	239	309	20	376	273	209A
Middle	81	456	340	21	348	299	256A
Late	63	303	289	33	402	398	250A
Total†	60a	332bc	313b	25a	376c	323bc	

† Mean separations are within species and across years. Values with same letter are not significantly different (α = 0.05, Tukey-Kramer adjusted comparisons).

Table 4. Test of fixed effects on lentil grain yield, combined 2009-2010 data†

Effect	Becker			Lamberton			Rosemount		
	F value	Pr > F	Sig.	F value	Pr > F	Sig.	F value	Pr > F	Sig.
Date (A)	10.46	0.0058	**	5.96	0.0260	*	27.21	0.0003	**
Variety (B)	72.91	<.0001	**	8.80	0.0065	**	15.80	0.0006	**
Weeding (C)	2.55	0.1364		154.53	<.0001	**	106.32	<.0001	**
Year (D)	8.17	0.0460	*	14.97	0.0180	*	3.98	0.1166	
A x B	5.84	0.0089	**	0.31	0.7383		2.74	0.0854	
A x C	0.08	0.9264		0.71	0.5136		0.84	0.4549	
B x C	0.78	0.3851		3.11	0.0902		2.77	0.1099	
A x D	0.19	0.8339		2.29	0.1638		19.52	0.0008	**
B x D	2.19	0.1521		0.46	0.5053		1.23	0.2792	
C x D	0.27	0.6096		64.48	<.0001	**	15.32	0.0021	**
A x B x C	0.62	0.5445		1.83	0.1820		0.76	0.4780	
B x C x D	0.00	0.9821		0.00	0.9593		0.04	0.8471	
A x C x D	1.23	0.3259		0.74	0.4990		1.53	0.2559	
A x B x D	0.50	0.6138		1.53	0.2362		0.33	0.7254	
AxBxCxD	0.12	0.8902		1.13	0.3402		0.82	0.4509	

† Includes data from Crimson and Pennell varieties only

* Significant at 0.05 level of probability

** Significant at 0.01 level of probability

Table 5. Lentil grain yields at three locations in 2009 and 2010 as affected by weeding, planting date, and variety.†

	Becker			Lamberton			Rosemount		
	2009	**2010**	**Mean**	**2009**	**2010**	**Mean**	**2009**	**2010**	**Mean**
Date	kg ha^{-1}								
Early	1492	952	1222a‡	348	404	376a	550a	129a	339
Middle	1129	810	970ab	181	322	252ab	241a	114a	177
Late	761	639	700b	77	181	129b	2b	85a	44
Total	1127	800	964	202	302	252	264	109	187
Weeded									
No	1107	767	937a	107a	3a	58	85a	4a	44
Yes	1148	834	991a	321b	601b	469	444b	214b	329
Variety									
Crimson	1295	991	1143a	261	431	346a	335	190	262a
Pennell	960	610	785b	144	173	158b	194	28	111b

† Includes data from Crimson and Pennell varieties only

‡ Mean separations are pooled over years except where treatment interactions with year were significant. Weeding by year interactions were significant ($\alpha = 0.05$) only at Rosemount and Lamberton; date by year interaction was significant only at Rosemount. Values with same letter are not different ($\alpha = 0.05$, Tukey-Kramer adjusted comparisons)

Table 6: Predicted yearly costs of organic field pea and lentil production†

Expense	Cost	
	Pea	**Lentil**
Equipment and Labor	— $ ha^{-1} —	
Field preparation: Tandem disk	22.91	22.91
Planting: 16 ft drill	29.75	29.75
Harvest: Swather	22.34	22.34
Harvest: Combine, pickup head for windrows	67.46	67.46
Seed		
Pea: 178 kg ha^{-1} @ \$0.88 kg^{-1}	197.68	
Lentil: 178 kg ha^{-1} @ \$1.10 kg^{-1}		247.11
Inoculant	12.36	12.36
Total	352.50	401.92

† Based upon calculations by Lazarus (2011)

Table 7: Price, production cost, and break-even yield, and observed yields of pea and lentil

	Price	Production cost	Break-even yield	Observed yield range†
	$ kg^{-1}	$ ha^{-1}	kg ha^{-1}	kg ha-1
Low-price Scenario				
Pea	0.42	352.5	833	1279-4775
Lentil	0.66	401.92	608	1-1756
High-price scenario				
Pea	3.51	352.5	101	1279-4775
Lentil	3.95	401.92	102	1-1756

†Minimum and maximum of early-planted unweeded treatments, averaged across replications within location, year, and variety.

Table 8: Analysis of variance of lentil grain yield and total (lentil + intercrop) grain yield by location, lentil variety, and intercrop†

	2009		2010	
	Lentil	**Total**	**Lentil**	**Total**
Location	*	*	*	*
Variety	*	ns	*	*
Intercrop	*	*	*	*
Location x Variety	ns	ns	*	*
Location x Intercrop	*	*	*	*
Variety x Intercrop	ns	ns	*	*
Location x Variety x Intercrop	ns	ns	*	*

† Asterisks indicate effects significant at $P < 0.05$

Table 9. Average lentil grain yield and total (lentil + intercrop) grain yield by year, location, intercrop treatment, and lentil variety.

Year		Becker Lentil		Becker Total		Lamberton Lentil		Lamberton Total		Rosemount Lentil		Rosemount Total	
		Dry weight, kg ha^{-1}											
2009	Oat	1303	a†	2151	a	40	a	2706	c	162	a	914	ab
	Wheat	1232	a	1447	a	113	a	2062	c	472	a	1593	bc
	Oilseed radish	1313	a	1401	a	13	a	859	b	159	a	432	a
	Winter rye	1645	a	1645	a	88	a	88	ab	350	a	350	a
	Rapid-cycling brassica	1617	a	1617	a	162	a	162	ab	195	a	195	a
	Unweeded control	1550	a	1550	a	21	a	21	a	406	a	406	a
	Weeded control	1515	a	1515	a	464	a	464	ab	1814	b	1814	c
	Total	1454		1628		129		927		508		815	
2010	Crimson												
	Oat	928	a	956	a	16	a	87	a	31	a	75	a
	Wheat	1203	ab	1209	ab	45	a	45	a	161	ab	353	ab
	Oilseed radish	1375	ab	1376	ab	8	a	19	a	61	a	82	a
	Winter rye	1239	ab	1239	ab	0	a	0	a	211	ab	211	ab
	Rapid-cycling brassica	1146	ab	1146	ab	3	a	3	a	35	a	35	a
	Unweeded control	1530	b	1530	b	46	a	46	a	151	ab	151	ab
	Weeded control	1485	b	1485	b	1125	b	1125	b	577	b	577	b
	Total	1272		1277		178		189		175		212	
	Pennell												
	Oat	617	ab	634	ab	3	a	131	a	3	a	42	a
	Wheat	620	ab	641	ab	44	a	126	a	31	a	172	a
	Oilseed radish	885	ab	888	ab	1	a	17	a	11	a	48	a
	Winter rye	455	a	455	a	1	a	1	a	7	a	7	a
	Rapid-cycling brassica	467	a	467	a	3	a	3	a	11	a	11	a
	Unweeded control	1021	b	1021	b	4	a	4	a	3	a	3	a
	Weeded control	994	b	994	b	12	a	12	a	56	a	56	a
	Total	723		729		8		39		17		50	

†Mean separations are within columns and within years. 2010 mean separations are within lentil variety. Values with same letter are not significantly different (α = 0.05, Tukey-Kramer adjusted comparisons).

Table 10. Average weed biomass and total (weed + intercrop) biomass in lentil plots by location and year

Year		Becker				Lamberton				Rosemount			
		Weed		Total		Weed		Total		Weed		Total	
		Dry weight, $g\ m^{-2}$											
2009	Winter rye	9	a†	35	a	370	a	453	a	322	a	439	a
	Rapid-cycling brassica	30	a	35	a	603	b	640	ab	474	ab	480	a
	Unweeded control	39	a	39	a	789	b	789	b	554	b	554	a
2010	Winter rye	5	a	155	a	566	a	631	a	81	a	196	a
	Rapid-cycling brassica	4	a	9	a	583	a	619	a	422	b	454	ab
	Unweeded control	4	a	4	a	800	b	800	a	645	c	645	b

†Mean separations are within columns and within years. Values with same letter are not significantly different (α = 0.05, Tukey-Kramer adjusted comparisons).

Table 11: Analysis of variance of pea grain yield and total (pea + intercrop) grain yield by location, pea variety, and intercrop†

	2009		2010	
	Pea	Total	Pea	Total
Location	ns	ns	ns	ns
Variety	ns	ns	ns	ns
Intercrop	*	*	*	*
Location x Variety	ns	ns	*	*
Location x Intercrop	*	*	*	*
Variety x Intercrop	ns	ns	ns	ns
Location x Variety x Intercrop	ns	ns	ns	ns

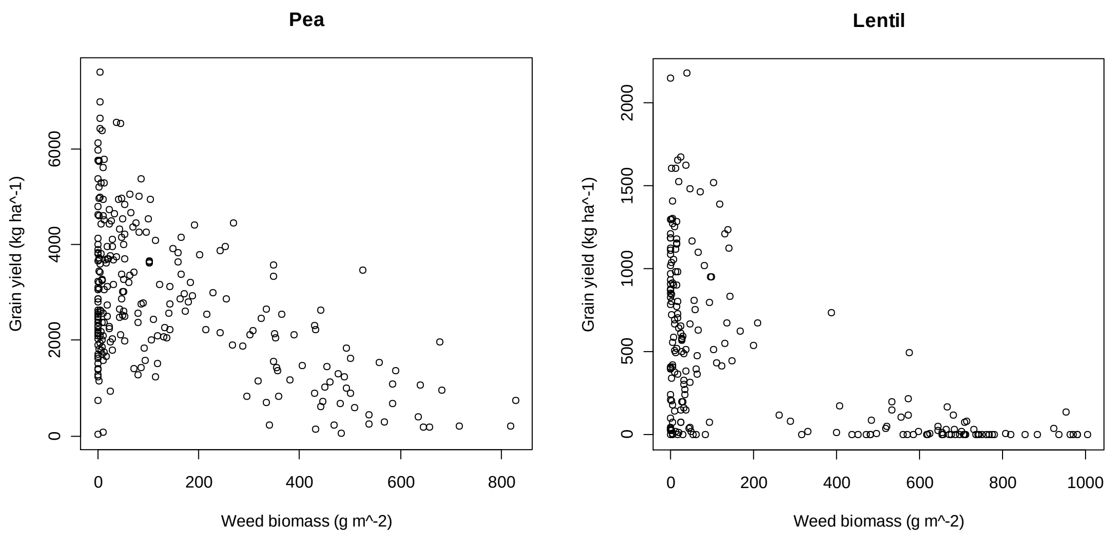
† Asterisks indicate effects significant at $P < 0.05$

Table 12. Average pea grain yield and total (pea + intercrop) grain yield by year, location, and intercrop treatment.

Year		Becker				Lamberton				Rosemount			
		Pea		Total		Pea		Total		Pea		Total	
		Dry weight, kg ha^{-1}											
2009	Oat	2201	a†	2396	a	1421	a	3383	ab	1786	a	2288	a
	Wheat	2263	a	2429	a	1816	ab	2801	ab	1593	a	2024	a
	Oilseed radish	2378	a	2426	a	1947	ab	2597	a	2068	a	2312	a
	Winter rye	2249	a	2249	a	2850	abc	2850	ab	2627	a	2627	a
	Rapid-cycling brassica	2735	a	2735	a	2897	c	2897	ab	2709	a	2709	a
	Unweeded control	2662	a	2662	a	3607	c	3607	ab	2349	a	2349	a
	Weeded control	2937	a	2937	a	3748	c	3748	b	4335	b	4335	b
	Total	2489		2548		2612		3126		2495		2663	
2010	Oat	1628	a	1694	a	1624	a	1764	a	688	a	779	a
	Wheat	1676	a	1678	a	1131	a	1225	a	1944	ab	2006	ab
	Oilseed Radish	2280	a	2281	a	2009	a	2039	a	2129	ab	2151	ab
	Winter Rye	1731	a	1731	a	1983	a	1983	a	3055	b	3055	b
	Rapid-cycling brassica	2063	a	2063	a	2340	a	2340	a	2991	b	2991	b
	Unweeded control	2370	a	2370	a	2229	a	2229	a	2570	b	2585	b
	Weeded control	2390	a	2390	a	4553	b	4553	b	3416	b	3416	b
	Total	2020		2013		2267		2305		2393		2420	

†Mean separations are within columns and within years. 2010 mean separations are within lentil variety. Values with same letter are not significantly different (α = 0.05, Tukey-Kramer adjusted comparisons).

Figure 1. Lentil and pea yield by weed biomass at harvest, pooled years, locations, and weeding treatments.



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Appendix. Average lentil grain yields in 2009 and 2010 by location, variety, planting date, and weeding treatment

Year		Becker			Lamberton			Rosemount		
		Early	Middle	Late	Early	Middle	Late	Early	Middle	Late
		kg ha^{-1}								
2009	Unweeded									
	Crimson	1755	1090	972	107	212	43	100	89	1
	Pennell	1260	1023	541	127	107	12	278	41	0
	Richlea	2015	1050	897	125	93	131	444	52	0
	Riveland	1073	737	787	448	91	15	278	42	2
	Weeded									
	Crimson	1708	1364	883	683	356	212	1161	648	9
	Pennell	1246	1042	648	475	95	42	660	187	0
	Richlea	1927	1316	1303	928	517	343	1314	707	3
	Riveland	1428	1118	1079	508	119	161	1246	528	2
2010	Unweeded									
	Crimson	1054	968	796	3	6	0	7	14	2
	Pennell	704	671	406	0	1	10	1	2	0
	French	974	736	786	3	0	3	1	4	0
	Weeded									
	Crimson	1168	1011	950	1188	820	569	401	389	329
	Pennell	881	591	404	423	462	143	106	49	8
	French	1113	987	815	881	862	294	450	376	123