Productivity and nitrogen benefits of late-season legume cover crops in organic wheat production

Harun Cicek[1], Martin H. Entz[1], Joanne R. Thiessen Martens[1], and Paul R. Bullock[2]

[1]Department of Plant Science, University of Manitoba, Winnipeg, Manitoba, Canada R3T 2N2; and [2]Department of Soil Science, University of Manitoba, Winnipeg, Manitoba, Canada R3T 2N2.
Received 28 April 2013, accepted 21 January 2014. Published on the web 5 February 2014.

Cicek, H., Entz, M. H., Thiessen Martens, J. R. and Bullock, P. R. 2014. **Productivity and nitrogen benefits of late-season legume cover crops in organic wheat production**. Can. J. Plant Sci. **94**: 771–783. When full-season cover crops are used in stockless organic rotations, cash crop production is compromised. Including winter cereals in rotations can widen the growing season window and create a niche for late-season cover crops. We investigated the establishment and biomass production of relay-cropped red clover (*Trifolium pratense* L.) and sweet clover (*Melilotus officinalis* L. 'Norgold') and double-cropped cowpea (*Vigna unguiculata* L. 'Iron and Clay'), hairy vetch (*Vicia villosa* L.), lentil (*Lens culinaris* L. 'Indianhead'), soybean (*Glycine max* L. 'Prudence'), pea (*Pisum sativum* L. '40–10'), and oil seed radish (*Raphanus sativus* L.) as well as wheat response to these crops under reduced tillage (RT) and conventional tillage (CT) at three locations in Manitoba, Canada. Red clover, sweet clover and pea produced from 737 to 4075 and 93 to 1453 and 160 to 2357 kg ha^{-1}of biomass, respectively. All double crops, with the exception of soybean at 2 site years, established successfully under both RT and CT. The presence of cover crops increased wheat N uptake at stem elongation, maturity and yield, even when the biomass production of cover crops was modest. We conclude that late-season cover crops enhance the following wheat yield and facilitate reduced tillage in organic crop production.

Key words: Double and relay cover cropping, organic wheat, nitrogen, reduced tillage

Cicek, H., Entz, M. H., Thiessen Martens, J. R. et Bullock, P. R. 2014. **Avantages d'une culture-abri de légumineuses en fin de saison pour la production de blé biologique sur les plans de la productivité et de l'apport d'azote**. Can. J. Plant Sci. **94**: 771–783. L'usage d'une culture-abri toute la saison avec les assolements biologiques, dans les systèmes de production à stock zéro, compromet le rendement des cultures commerciales. Intégrer des céréales d'hiver à l'assolement pourrait élargir la période végétative et permettre l'établissement de cultures-abris en fin de saison. Les auteurs se sont intéressés à l'établissement et à la production de biomasse du trèfle rouge (*Trifolium pratense* L.) et du mélilot (*Melilotus officinalis* L. Norgold) en culture relais, ainsi que de la dolique (*Vigna unguiculata* L. Iron and Clay), de la vesce velue (*Vicia villosa* L.), de la lentille (*Lens culinaris* L. Indianhead), du soja (*Glycine max* L. Prudence), du pois (*Pisum sativum* L. 40–10) et du radis (*Raphanus sativus* L) en double culture, de même qu'à la réaction du blé à ces cultures, dans un régime à travail réduit du sol (TR) ou à labours classiques (LC). L'expérience s'est déroulée à trois endroits, au Manitoba (Canada). Le trèfle rouge, le mélilot et le pois ont donné respectivement de 737 à 4 075, de 93 à 1 453 et de 160 à 2 357 kg de biomasse par hectare. Toutes les doubles cultures, sauf le soja, se sont bien établies aux deux années-sites sous les régimes TR et LC. La présence d'une culture-abri favorise l'absorption du N par le blé à l'élongation de la tige, et en améliore la maturité et le rendement même si la culture-abri produit une quantité modeste de biomasse. On en conclut que les cultures-abris de fin de saison rehaussent le rendement du blé la saison suivante et facilitent la réduction du travail du sol en agriculture biologique.

Mots clés: Blé biologique, azote, travail réduit

A cover crop may be defined as any crop grown to provide soil cover regardless of whether it is later soil incorporated. Organic farms in the Northern Great Plains (NGP) of North America typically include legume cover crops in rotation to maintain soil fertility. However, growing a cover crop for the full season incurs the loss of that year's cash crop. Cover cropping systems that are in synchrony with the intensive annual organic crop production are required for organic farmers. Relay and double crop systems exploit the heat and precipitation resources after the main crop harvest. Therefore, organic farmers using relay and double-cropping techniques may be able to harvest a cash crop and benefit from a cover crop within the same growing season.

Late-season legume cover crops were defined as cover crops that are grown alongside or after the cash crop within the same growing season. The terms "double crop" and "relay crop" are both considered as late-season legume cover crops. Double-cropping involves seeding a cover crop after the main crop harvest, whereas relay-cropping entails seeding cover crops into an established crop. Although in some regions relay and double cover crop products can be harvested (i.e., double-cropped soybeans after winter wheat in Kansas and Missouri), in

Abbreviations: **CT**, conventional tillage; **GDD**, growing degree days; **NGP**, Northen Great Plains; **Notre DL**, Notre Dame de Lourdes; **RT**, reduced tillage the NGP they are commonly grown to provide soil cover, fix atmospheric nitrogen and improve the overall soil health. In this paper we consider relay and double crops as soil fertility (i.e., nitrogen) building crops.

Winter cereals are typically harvested earlier than spring-seeded crops providing a larger window of opportunity for relay and double crops to capture heat and precipitation. Thiessen Martens and Entz (2001) estimated that in systems including winter wheat there is sufficient heat and precipitation to grow double and relay cover crops in south-central Manitoba, but precipitation may be the limiting factor in southern Saskatchewan and Alberta. Nadler and Bullock (2011) analyzed 80 yr of weather data (1921 to 2000) from 12 stations across the Canadian prairies and found that corn heat unit accumulation and precipitation have increased in the southern parts of the Canadian prairies. Furthermore, as a result of extreme weather conditions and favorable markets, the areas seeded to winter wheat (*Triticum aestivum* L.) and fall rye (*Secale cereale* L.) have been increasing (Statistics Canada 2013). In spite of these, double- and relay-cropping in organic agriculture have received little attention in the NGP region. Most research on cover crops in conventional systems focussed on the fallow replacement potential of legume cover crops (Zentner et al. 2004). In conventional systems Thiessen Martens et al. (2001) used black lentil (*Lens culinaris* L.) and chickling vetch (*Lathyrus sativus* L.) as double crops, but most other studies used cover crops as full season fertility building crops (Vaisman et al. 2011). Studies from Northern Europe reported the effects of under-sown clovers on weeds and wheat yield (Hartl 1989; Brandsaeter et al. 2012; Sjursen et al. 2012) as well as on soil nitrate (Plaza 2011).

Relay-cropping, especially using red clover (*Trifolium pratense* L.) and alfalfa (*Medicago sativa* L.), has received more attention than double-cropping in temperate regions. Production factors such as competition from main crop cultivar type and light interception (Blaser et al. 2011), legume cultivar selection (Singer et al. 2006), optimal seeding rates (Blaser et al. 2007), moisture effect on establishment (Queen et al. 2009), seeding date (Blackshaw et al. 2010a), effect on companion crop species (Thiessen Martens et al. 2001) and the fertilizer replacement value of relay crops (Liebman et al. 2012) have been investigated under conventional systems. Most of these studies reported successful establishment of red clover, yet, biomass production varied greatly depending on the edaphic (i.e., soil), climatic (i.e., precipitation) and agronomic (i.e., companion crop type, seeding date) conditions.

Most of the aforementioned factors for production are relevant for the organic production systems as well, but the objectives for the inclusion of relay or double crops maybe different. Even though cover crop benefits such as soil erosion control, weed suppression, soil organic matter building are important for all farmers, N contribution benefits are particularly vital for organic farmers. Berry et al. (2002) argue that N is one of the key factors limiting the productivity of organic farms. Accordingly, the major expectation from a relay or double crop in organic systems is high biomass production and optimal biological N_2 fixation. Although N benefit is generally correlated with biomass production (Peoples et al. 2001) competition with other crops may increase the amount of biological N fixation. For instance, relay-cropped red clover has been shown to fix 20% more N_2 than monocropped red clover (Schipanski and Drinkwater 2011).

Organic land management relies heavily on tillage to control weeds and to mineralize N from green manures. There has been considerable work on reducing tillage in organic systems. Such attempts focus mainly on manipulations during the green manure or cover crop phase of the rotations (Peigné et al. 2007; Vaisman et al. 2011). As a result of better water retention in reduced tillage (RT) than in conventional tillage (CT) systems (Krauss et al. 2010), late-season cover crops may establish and produce more biomass under RT than under CT. While N mineralization in long-term no-till soils is faster than in conventional tilled soils (Soon et al. 2011), in the short-term N mineralization is slower in RT systems than in CT systems (Vaisman et al. 2011).

It may be possible to reduce tillage in short-term rotations without an N penalty. However, this requires a plant biomass with low C:N ratio to be present, because net mineralization from indigenous soil N sources increases when the crop residue C:N ratio is low (i.e., C:N $<$20:1; Bremer and van Kessel 1992). Therefore, a question of interest is whether low C:N biomass from late-season cover crops may be able to provide sufficient N to offset the slower mineralization from RT. No NGP studies have investigated reduced tillage in organic late-season cover crop systems.

There is a lack of knowledge as to which species can be employed in double- and relay-cropping systems of western Canada. A study was initiated in southern Manitoba to identify the successful species that can be used in double- and relay-cropping systems under organic management. Specifically, we investigated establishment, growth and N benefits of various double- and relay-cropped species under conventional and reduced tillage management. We anticipated that the double crops grown in reduced tillage plots will produce more biomass than those managed under conventional tillage. We also hypothesized that the N benefits of legumes (measured as wheat N uptake and yield) under reduced tillage will be less than those under conventionally managed legumes, but that as cover crop legume biomass increases, the yield penalty from reducing tillage would decrease. The information generated from this study will enhance our ability to design diversified agroecosystems that are nutrient-use efficient.

MATERIALS AND METHODS

Site Description

This experiment was conducted at three locations in Manitoba, with different soil and climatic conditions: University of Manitoba Ian Morrison Research Farm in Carman (lat. 49°29'N, long. 98°0'W), University of Manitoba Glenlea Research station (lat. 49°64'N, long. 97°14'W), and, DeRuyck's Certified Organic Farm in Notre Dame de Lourdes (lat. 49°54'N, long. 98°76'W). The experimental sites at Glenlea and Carman were not certified organic but have been managed based on organic agriculture principles since 1992 and 2003, respectively. No inputs were applied to any of the treatments. Based on soil analyses from the depth of 0–30 cm, the soil at Carman was an Orthic Black Chernozem with a fine sandy loam texture, pH of 6.2, and an organic matter content of 25 g kg^{-1}. Glenlea soils were Rego Black Chernozem with a pH of 7.4, and an organic matter content of 77 g kg^{-1}. At Notre Dame de Lourdes (Notre DL) the soil was Orthic Dark Gray Chernozem sandy clay loam, having a pH of 7.4 and an organic matter content of 57 g kg^{-1}.

Background soil samples were taken before the experiment to characterize the nitrate (NO_3^-) levels of the experimental plots. Soil N samples were taken to 60 cm depth with a Dutch auger. Soil nitrate was extracted with KCl solution and analyzed for nitrate (NO_3^-) using the cadmium reduction method (Maynard et al. 2007). At Carman and Notre DL in 2009, soil samples were taken in the spring and contained 34 and 105 kg ha^{-1} of NO_3^-, respectively. Soil NO_3^- levels taken from CT control plots from the same sites in the following spring were 42 and 39 kg ha^{-1}, respectively. For Glenlea and Carman 2008 trials we failed to take background NO_3^- samples, but the samples taken from CT control plots at these sites in the following spring were 37 and 51 kg ha^{-1} of NO_3^-, respectively.

The experiment started in 2008 at Carman and Glenlea locations. In 2009, as a result of floods in Glenlea, the experiment was conducted at Carman and Notre DL. Wheat was used as a test crop for the experiments in 2008 and 2009. For the experiments that started in 2010 and 2011, only the establishment and biomass production of cover crops were investigated. Each experiment started with fall rye (*Secale cereale* L. 'Remington') cash crop and late-season cover crops in year 1. Fall rye was seeded using a JT-A10 air-drill seeder (R-Tech Industries Ltd., Homewood, MB) with a row spacing of 20 cm and a seeding rate of 100 kg ha^{-1}. The fall rye grain was harvested few days before the seeding of double crops as indicated in Table 1. Wintersteiger (Wintersteiger Inc., Saskatoon, SK) plot harvester was used for fall rye grain harvest from the whole plot.

The relay crops were red clover (*Trifolium pratense* L.) and sweet clover (*Melilotus officinalis* L. 'Norgold') while double crops were cowpea (*Vigna unguiculata* L. 'Iron and Clay'), hairy vetch (*Vicia villosa* L.), lentil (*Lens culinaris* L. 'Indianhead'), soybean (*Glycine max* L. 'Prudence'), pea (*Pisum sativum* L. '40-10'), and oil seed radish (*Raphanus sativus* L.). The seeding rates and seeding and termination dates of double and relay crops are presented in Table 1. Although the main objectives of this study revolve around N benefit from legume cover crops, oil seed radish was included in the study because of its widespread usage by farmers in NGP. Oil seed radish is particularly suitable in situations where; (i) soil fertility is high, (ii) there is a need to produce forage for livestock, and, (iii) where there are soil compaction issues (Williams and Weil 2004). Hairy vetch was not used in the Notre DL site due to the farmer's concern over hairy vetch's potential to become a volunteer crop (weed) in the following years. In 2010 we only seeded pea, lentil and hairy vetch, and in 2011, only

Table 1. Seeding and termination dates for relay and double crops from 2008 to 2011 at Carman, Glenlea and Notre Dame de Lourdes (Notre DL)

		Seeding date/termination date (month-day/month-day)							
		2008		2009		2010		2011	
Cover crops	Seeding rate (kg ha^{-1})	Carman	Glenlea	Carman	Notre DL	Carman	Glenlea	Carman	Notre DL
Relay crops									
Red clover	10	4-16/10-9	4-18/10-4	4-29/10-24	4-29/10-24	–	–	5-6/10-14	5-16/10-20
Sweet clover	10	4-16/10-9	4-18/10-4	4-29/10-24	4-29/10-24	–	–	5-6/10-14	5-16/10-20
Double crops									
Pea	125	8-20/10-9	8-20/10-4	8-26/10-24	9-4/10-24	8-11/10-21	8-11/10-21	8-8/10-14	8-17/10-20
Lentil	45	8-18/10-9	8-20/10-4	8-26/10-24	9-4/10-24	–	8-11/10-21	–	–
Hairy vetch	35	8-18/10-9	8-20/10-4	8-26/10-24	–	–	8-11/10-21	–	–
Soybean	90	8-18/10-9	8-20/10-4	8-26/10-24	9-4/10-24	–	–	–	–
Oil seed radish	20	8-20/10-9	8-20/10-4	8-26/10-24	9-4/10-24	–	–	–	–
Cowpea	80	8-18/10-9	8-20/10-4	8-26/10-24	9-4/10-24	–	–	–	–

red clover, sweet clover, and pea based on their successful establishment in the previous years.

Legumes were all inoculated with the appropriate *Rhizobium* species. Cell-Tech liquid inoculator (Novozymes, Franklinton, NC) was used for soybean and cowpea. For pea, lentil, hairy vetch and faba bean we used NitraStic-C peat based inoculant (Novozymes, Franklinton, NC). Both inoculants were applied at the manufacturer's recommended application rate of 75 mL of inoculant per 27 kg of seed. Red clover and sweet clover were inoculated with powder inoculant Nitragin Gold (Novozymes, Franklinton, NC) using manufacturer's recommended application rate of 19 kg of inoculant per 2273 kg of seed.

Relay crops were hand broadcasted into fall rye as soon as the fields were dry enough to handle traffic in the spring. Upon broadcasting soil was harrowed for better relay crop seed to soil contact. Double crops were seeded immediately after the fall rye grain harvest using a no-till disc drill (Fabro Enterprises Ltd., Swift Current, SK) with a row spacing of 15 cm and a depth setting of 4 cm. Control plots contained no cover crops and weeds were managed with tillage in conventional tilled plots. Weeds in reduced tillage plots were not managed. Relay and double crops were terminated using a rototiller.

Tillage regimes were RT and CT. Tillage regimes differed in terms of tillage before seeding (seeding into fall rye stubble vs. seeding after the tillage of fall rye stubble) and the timing of cover crop incorporation (autumn vs. spring incorporation). In the RT double crop system, double crops were seeded into rye residue with no preseeding tillage, and the land was not tilled until springtime the following year. In the CT double crop system, rye residue was tilled before seeding the double crops. Further, these plots were tilled in the autumn after double crop growth. Since relay crops were hand broadcasted there were no differences in seeding method for relay crops. Thus, RT relay crops were spring incorporated (immediately before wheat seeding) and CT relay crops were tilled in late fall of the rye year and again immediately before wheat seeding. Therefore, RT plots were tilled only once (immediately before spring wheat seeding) and CT plots were tilled three times before wheat seeding.

Wheat (*Triticum aestivum* L. 'Kane') was seeded (122 kg ha^{-1}) in the spring following the termination of relay and double crops as a test crop. Wheat was seeded using a JT-A10 air-drill seeder (R-Tech Industries Ltd. Homewood, MB) with a row spacing of 20 cm. The subplot size was 2 m by 8 m.

Data collection

Fall rye biomass (grain + straw) samples were taken at maturity using a 1-m^2 quadrat randomly placed in each of the four replicates. The samples were dried for 2 d at 60°C and weighed for dry matter content. The reported biomass numbers are the average weight of four replicates.

Crop establishment counts for relay crops were collected on two dates (except in 2008) to monitor progressive emergence from three randomly selected spots using a 0.0625-m^2 quadrat. Above-ground biomass of relay crops was collected from 2×0.25-m^2 areas within each plot, while double crops were collected from 2×0.4-m^2 areas within each plot. Relay crop biomass samples in RT plots were collected in the autumn and in the spring. Spring sampling was done when relay crops survived winter to produce more biomass as in 2009 Notre DL and Carman. Double crops were counted only once after emergence using a 1-m ruler and counting both sides of the ruler at two randomly selected spots in each plot. Above-ground biomass of double crops was collected from 2×0.4-m^2 areas within each plot. Double crop biomass samples were taken only once, in mid-October.

A wheat test crop in year 2 was only deployed for the 2008 and 2009 experiments. Wheat biomass samples at Carman were taken at stem elongation and maturity from 2×0.4-m^2 areas in each plot. At Glenlea, wheat biomass samples were collected at stem elongation and soft dough stages. At Glenlea, nearby wheat fields were being destroyed by migrating geese, therefore, samples were taken earlier, at soft dough, before extensive damage could be done by geese. Wheat grain for yield estimation was collected from the whole plot using a Wintersteiger (Wintersteiger Inc., Saskatoon, SK) plot harvester. All samples were dried for 2 d at 60°C and weighed for dry matter content.

Dry wheat and cover crop biomass samples were ground with a Wiley Mill (No. 1 Arthur H. Thomas Co., Philadelphia, PA). Wheat grains were ground with a Cyclone Lab Sample Mill (UDY Corporation, Fort Collins, CO). All ground samples were subsampled and analyzed for N concentration by combustion analysis using a LECO FP-528 (LECO, St. Joseph, MI). Wheat N uptake at stem elongation, soft dough (Glenlea) and maturity (Carman and Notre DL) were calculated as the product of biomass production (kg ha^{-1}) and the percent N content of the ground wheat biomass sample. Wheat grain percent N content was multiplied by 5.7 for the estimation of wheat grain protein (Jones 1941).

All weather-related data were obtained from the Environment Canada database (Environment Canada 2012). Growing degree days (GDD) were calculated using 3°C as a base temperature with the formula:

$$\text{GDD} = [(\text{max temperature} + \text{minimum temperature})/2)] - 3 \qquad (1)$$

Since most of the crops used in our study were cool season crops, 3°C was chosen as the base temperature.

Statistical Analysis

The experimental design was a randomized complete block with four replicates in a split plot arrangement.

The main plots were tillage regime and the subplots were cover crop type. Control plots contained no cover crops. SAS software (SAS Institute, Inc. 2001) PROC Mixed procedure was used for data analysis. We used ANOVA and considered treatment effects as fixed effects and replicates as random effects for all measurements. Relay crop biomass production was analyzed separately than double crops. Assumptions of ANOVA were tested by using the PROC Univariate procedure. Differences were considered significant at $P < 0.05$ and means were separated using a Fisher protected LSD test. Planned comparisons were analyzed using the ''Estimate'' statement in SAS. A linear regression model was fitted to explore the relationship between double and relay crop biomass production and wheat N uptake at stem elongation and maturity.

RESULTS AND DISCUSSION

Climate and Field Conditions

Growing season air temperatures, precipitation and GDD in all study years and sites deviated widely from long-term averages (Tables 2 and 3). Lower than average temperatures and GDD were recorded in 2009 at Carman and Notre DL. In 2010 precipitation was almost double the 30-yr average. In 2010 and 2011, growing season air temperatures were much higher than the 30-yr average. As a result of GDD accumulation, fall rye in 2010 and 2011 was harvested much earlier than in other years and double crops were seeded by Aug. 08 in Carman (Tables 1 and 2). In a previous Manitoba study, as a result of warmer growing season temperatures, Thiessen Martens et al. (2001) seeded double crops after fall rye on Jul. 29 in 1998 and Aug. 10 in 1999.

Fall rye above-ground biomass values were 13 788 kg ha^{-1} at Glenlea, 15 040 kg ha^{-1} at Carman in 2008, 13 474 kg ha^{-1} at Carman in 2009, 10 901 kg ha^{-1} at Notre DL in 2009, 11 657 kg ha^{-1} at Carman in 2011 and 15 945 kg ha^{-1} at Notre DL in 2011. Biomass production of fall rye in this study is comparable to an earlier Manitoba study where fall rye biomass ranged from 7611 to 15 375 kg ha^{-1} (Thiessen Martens et al. 2001).

Relay Crop Establishment and Dry Matter Production

Successful relay crop establishment was observed at 5 of 6 site years for red clover and 3 of 6 site years for sweet clover (Table 4). Both crops failed to establish at Carman in 2008, presumably due to low precipitation from April to June (Table 3). Sweet clover also failed to establish at Notre DL in 2011, perhaps due to a very dense fall rye canopy (15 945 kg ha^{-1}) competing for light and moisture. Queen et al. (2009) observed reduction in the relay-cropped red clover establishment with decreasing light penetration in wheat. Negative effects of limited soil moisture on relay-cropped red clover establishment was previously reported by Singer et al. (2006) but there are no previous reports for sweet clover when grown as a relay crop.

At some locations, red clover plant density increased from early June to July, perhaps as a result of the hard seed coat of red clover delaying early germination and the favorable growing conditions later in the spring facilitating germination. Queen et al. (2009) noted that relay-cropped red clover plant density progressively increased until 4–6 wk after planting. They also reported that when precipitation was higher than long-term normals, red clover plant density was more stable during all developmental stages of wheat. In the present study, red clover had significantly higher plant densities than sweet clover at 2 of 5 site years.

Despite the high seeding rates used in this study (400 seeds m^{-2}) less than 25% of the seeds developed into seedlings. Blackshaw et al. (2010a) used around 200 seeds m^{-2} for red clover, and the plant densities in that study were similar to ours. Blaser et al. (2011) and Singer et al. (2006) found that red clover biomass production is independent of plant population densities when there were more than 30 plants m^{-2}.

In all site years, except at Carman in 2009, red clover produced significantly more biomass than sweet clover (Table 6). Red clover dry matter biomass production ranged from 737 to 4075 kg ha^{-1} and was greater than previous observations in Manitoba (605 to 1804 kg ha^{-1}; Thiessen Martens et al. 2001), or Alberta (10 to 1420 kg ha^{-1}; Blackshaw et al. 2010a) studies. However, our findings are in agreement with other works from wetter regions such as Ontario (Vyn et al. 2000) and Michigan (Hesterman et al. 1992) reporting 1930 to 4020 kg ha^{-1} and 2250 to 5500 kg ha^{-1} biomass production, respectively. Although there seems to be a trend based on the regional precipitation gradient (i.e., more precipitation, more biomass), biomass production of clovers in our experiment did not respond to fluctuating growing season precipitation (Tables 3 and 6). Rather, there was an evidence of ''carry-over'' soil moisture from previous year to increase biomass production. For instance, in 2011, growing season precipitation at Carman was 90 mm lower than the 30-yr average, but red clover produced 4075 kg ha^{-1} of biomass, perhaps as a result of high precipitation in 2010 recharging soil moisture beyond crop requirements in 2011. In 2009, Carman growing season precipitation was exactly the 30-yr average (386 mm) but red clover produced only 850 kg ha^{-1} biomass. Similarly, in 2008, growing season precipitation at Glenlea (397 mm) was close to the 30-yr average (416 mm) and red clover produced 3696 kg ha^{-1} of biomass. Besides water availability, main crop competition and late-season heat availability are also potential influencing factors for red clover biomass production. Queen et al. (2009) argued that, besides availability of cheap fertilizers, this apparent unpredictability in relay crop biomass production has prevented the wider adoption of relay-cropping.

Table 2. Average monthly growing season air temperatures, 30-yr average air temperatures and monthly growing season growing degree days (GDD) from 2008 to 2011 for Carman, Glenlea and Notre Dame de Lourdes (Notre DL)

	Temperature (°C)						GDD			
	2008	2009	2010	2011	30-yr avg.[z]		2008	2009	2010	2011
Month	Carman						Carman			
April	3.4	2.9	8.7	4.5	4.2		56	49	169	68
May	8.9	8.5	11.6	10.4	12.5		185	174	264	235
June	15.5	15.4	16.3	16.7	16.9		369	384	420	430
July	18.2	16.9	19.6	20.3	19.4		471	415	515	536
August	19.1	17.1	18.7	19.3	18.2		498	436	487	503
September	13.0	17.3	11.8	14.0	12.2		298	427	265	329
October	6.6	3.6	8.3	8.2	5.5		115	50	170	167
Total							1990	1934	2290	2268
					30-yr avg.					
	Glenlea	Notre DL	Glenlea	Notre DL	Glenlea	Notre DL	Glenlea	Notre DL	Glenlea	Notre DL
April	3.2	2.5	8.5	3.7	4.2	4.1	50	48	154	61
May	9.3	9.2	12.0	10.1	12.4	12.8	182	195	266	225
June	16.0	17.3	16.3	21.0	17.0	17.0	382	430	392	537
July	18.2	16.7	19.6	20.4	19.3	19.9	457	430	516	537
August	19.6	17.4	18.9	20.1	18.4	18.8	480	447	491	528
September	10.9	18.0	11.0	14.9	12.2	12.8	395	450	251	357
October	6.0	3.5	8.1	8.6	5.1	6.0	104	48	168	179
Total							2050	2048	2239	2425

[z]From 1971 to 2000 for Glenlea and Notre DL; from 1961 to 1990 for Carman (Environment Canada 2013).

Double Crop Establishment and Dry Matter Production

Double crops were seeded immediately following fall rye harvest after either tillage (CT) or in untilled soil (RT). For most crops, years, and locations, tillage regime did not significantly influence establishment (Table 5). There was a tillage regime × crop species interaction at Carman in 2008 and at Notre DL in 2009, where, unlike other crops, pea had significantly higher plant population densities under CT than under RT (77 vs. 61 and 30 vs.

Table 3. Average growing season monthly precipitation from 2008 to 2011 and the 30-yr average for Carman, Glenlea and Notre Dame de Lourdes (Notre DL)

	Precipitation (mm)					
	2008	2009	2010	2011	30-yr avg.[z]	
Month	Carman					
April	22	23	35	44	42	
May	34	74	159	72	53	
June	85	127	63	59	73	
July	38	62	48	38	69	
August	55	53	138	12	65	
September	93	18	107	65	49	
October	72	28	57	8	34	
Total	398	386	607	297	386	
					30-yr avg.	
	Glenlea	Notre DL	Glenlea	Notre DL[y]	Glenlea	Notre DL
April	14	20	32	–	23	22
May	44	72	213	170	62	57
June	103	54	74	58	94	93
July	36	54	102	18	80	75
August	97	66	112	86	68	67
September	54	22	96	46	54	55
October	49	55	52	13	35	32
Total	397	344	681	391	416	403

[z]From 1971 to 2000 for Glenlea and Notre DL; from 1961 to 1990 for Carman (Environment Canada 2013).
[y]Precipitation information provided by Gerard DeRuyck based on on-farm rain gauge.

Table 4. Relay crop plant population densities for one date in 2008 and for two dates in 2009 and 2011 at Carman, Glenlea and Notre Dame de Lourdes (Notre DL)

	2008		2009				2011			
	Glenlea	Carman	Carman		Notre DL		Carman		Notre DL	
Relay crop	Jun. 02	Jun. 02	Jun. 01	Jun. 15	Jun. 01	Jun. 15	Jun. 06	Jul. 04.	Jun. 06	Jul. 12
	(plants m^{-2})									
Red clover	87	0	34	54	44	84*a*	64*a*	85*a*	35*a*	99*a*
Sweet clover	66	0	38	41	59	69*b*	29*b*	15*b*	8*b*	5*b*
ANOVA (*P* values)	0.189	n/a	0.646	0.333	0.158	0.047	0.049	<0.0001	0.001	0.003

a, *b* Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level of significance.

18 plants m^{-2} respectively; Table 5). A similar trend was observed for oilseed radish at Notre DL in 2009. Very high levels of fall rye residue may have been responsible for reduced establishment of double crops in RT plots at Notre DL in 2009.

Among double crops, pea consistently produced the highest biomass, ranging from 160 to 2357 kg ha^{-1} and averaging 890 kg ha^{-1} for the 8 site years (Table 6). The pea crop failed in only one circumstance. Poor pea establishment in the RT system at Notre DL in 2009, presumably due to excess fall rye residue, resulted in poor establishment (18 plants m^{-2}) and low biomass production (160 kg ha^{-1}) at this site.

No previous studies have investigated biomass production of pea as a late-season cover crop in Canada. When grown as a spring-seeded crop for 8 to 10 wk in Saskatchewan, pea produced an average 3008 kg ha^{-1} of biomass (Biederbeck et al. 1993). The growing period from seeding to killing frost in our experiment was less than 8 wk in most instances (Table 1). More importantly, pea reaches its maximum growth rate at the podding stage. Pea in our experiment rarely reached full bloom (data not shown) and grew under progressively declining temperatures.

Lentil biomass production ranged from 120 to 377 kg ha^{-1} over 4 site years and was lower than the 190 to 1051

Table 5. Double crop plant population densities from 2008 to 2011 at Carman, Glenlea and Notre Dame de Lourdes (Notre DL) for pea, hairy vetch, lentil, soybean, cowpea, and oil seed radish managed under reduced tillage and conventional tillage

	2008		2009		2010		2011	
Treatments	Glenlea	Carman	Carman	Notre DL	Carman	Glenlea	Carman	Notre DL
	(plants m^{-2})							
Reduced tillage								
Pea	68	61*d*	27	18*de*	109	104	56	51
Hairy vetch	68	66*cd*	21	–	–	–	–	–
Lentil	89	103*a*	50	74*a*	–	–	–	–
Soybean	28	31*e*	2	9*f*	–	–	–	–
Cowpea	23	40*e*	18	24*bcd*	–	–	–	–
Oil seed radish			17	12*ef*	–	–	–	–
Conventional tillage					–	–		–
Pea	75	77*bc*	30	30*bc*	119	87	53	41
Hairy vetch	55	69*cd*	23	–	–	–	–	–
Lentil	104	90*ab*	65	66*a*	–	–	–	–
Soybean	36	26*e*	2	9*f*	–	–	–	–
Cowpea	22	40*e*	23	21*bcd*	–	–	–	–
Oil seed radish	–[z]	–	36*b*		–	–	–	–
Reduced tillage	55	61	26		–	–	–	–
Conventional tillage	59	61	30		–	–	–	–
Source of variation	*P* values							
Crop species CS)	<0.0001[y]	<0.0001	<0.0001[x]	<0.0001	–	–	–	–
Tillage regime (TR)	0.1984	0.9644	0.0874	0.1682	0.7089	0.1088	0.8553	0.2617
CS × TR	0.4338	0.0474	0.8889	0.0013	–	–		–

[z]Crop not seeded.
[y]LSD for the effect of double crop is 6 plants m^{-2}.
[x]LSD for the effect of double crop is 9 plants m^{-2}.
a–f Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level of significance.

Table 6. Crop species and tillage regime effect on double and relay crop (red and sweet clover) biomass production from 2008 to 2011 at Carman, Glenlea and Notre Dame de Lourdes (Notre DL) for pea, hairy vetch, lentil, soybean, cowpea, and oil seed radish managed under reduced tillage (RT) and conventional tillage (CT)

	2008		2009		2010		2011	
Treatments	Glenlea	Carman	Carman	Notre DL[z]	Carman	Glenlea	Carman	Notre DL
	------ (kg ha^{-1}) ------							
Reduced tillage								
Pea	850*a*	978	520*ab*	160	1463*b*	905*a*	928	1320
Hairy vetch	281*cd*	315	225*d*	–	–	–	–	–
Lentil	173*de*	349	287*cd*	157	–	–	–	–
Soybean	145*e*	130	0	0	–	–	–	–
Cowpea	0[z]	11	470*ab*	0	–	–	–	–
Oil seed radish	–[y]	0	57*e*	67	–	–	–	–
Conventional tillage					–	–	–	–
Pea	534*b*	753	670*a*	570	2357*a*	354*b*	1303	1011
Hairy vetch	180*de*	262	650*a*	–	–	–	–	–
Lentil	314*c*	330	377*bc*	120	–	–	–	–
Soybean	142*e*	119	0		–	–	–	–
Cowpea	0	13	594*cd*	0	–	–	–	–
Oil seed radish	–	0	352*ab*	52	–	–	–	–
Means								
Reduced tillage	290*a*	295	312*b*	130	–	–	–	
Conventional tillage	234*b*	248	528*a*	211	–	–	–	
Source of variation	------ *P* values ------							
Crop species (CS)	<.0001	<.0001[x]	<.0001	0.0017[w]	–	–	–	
Tillage regime (TR)	0.0234	0.1356	0.0043	0.9423	0.0267	0.043	0.48	0.1122
CS × TR	0.0009	0.3720	<.0001	0.8982	–	–	–	
Relay crops	------ kg ha^{-1} ------							
Red clover	3696	0	850	2109	–	–	4075	737
Sweet clover	1450	0	460	1259	–	–	93	0
ANOVA (*P* values)	0.0002	N/A	0.2460	<0.0001	–	–	0.0021	n/a
Contrasts	------ *P* values ------							
Red clover vs. RT pea	0.0012	–	0.3326	0.0003	–	–	0.0002	0.0133
Red clover vs. CT pea	0.0007	–	0.9191	0.0016	–	–	0.0003	0.117

[z]Not included in ANOVA analysis.
[y]Crop not seeded.
[x]LSD for the effect of double crop is 181 kg ha^{-1}.
[w]LSD for the effect of double crop is 313 kg ha^{-1}.
a–e Experiments with significant crop species × tillage regime interaction means within a column followed by the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level of significance.

kg ha^{-1} reported by Thiessen Martens et al. (2001). Hairy vetch produced up to 650 kg ha^{-1} at Carman in 2009 (Table 6). Cowpea and soybean failed to produce biomass in 2 of 4 and 3 of 4 yr, respectively. In 2009 at Carman, however, cowpea produced 470 kg ha^{-1} of biomass, perhaps as a result of a warmer than normal September (Table 2). Oil seed radish produced less than 100 kg ha^{-1} in all site years. Therefore, among the double crops tested here, pea was the most consistent and highest biomass producer.

The presence of significant tillage regime by cover crop species interactions demonstrated that different cover crops responded to seedbed preparation management differently. For example, at Glenlea in 2008, RT pea produced more biomass than CT pea, while the opposite trend was observed for lentil (Table 6). At Carman in 2009, oil seed radish and hairy vetch responded with increased biomass production in CT versus RT, but other cover crops were not affected. Non-significant tillage regime × cover crop species interactions were observed at the other 2 site years where all double crop species were compared. These observations demonstrate no consistent effect of tillage regime on cover crop biomass production.

Pea managed under RT produced significantly more biomass than that managed under CT in 2 of 8 site years (at Glenlea 2008 and 2010), while no differences in pea biomass between CT and RT were observed at 4 of 8 site years (Table 6). At Notre DL in 2009 and at Carman in 2010 pea under CT produced more biomass than pea under RT. Working on a loam soil in North Dakota Carr et al. (2009) observed higher pea yield under no-till compared with tillage in 2 of 6 yr, with no difference in the remaining 4 yr. Working on sandy and clay loam soils in Manitoba, Borstlap and Entz (1994) observed higher pea biomass at maturity under zero tillage than CT. Both studies concluded that the positive impact of RT on pea

Table 7. Wheat N uptake at stem elongation and maturity following reduced tilled (RT) and conventional tilled (CT) red clover, sweet clover, pea, hairy vetch, lentil, soybean, cowpea, and oil seed radish and control at Carman, Glenlea and Notre Dame de Lourdes (Notre DL) Manitoba in 2009 and 2010

Treatments		Glenlea		Carman 2009		Carman 2010		Notre DL	
Tillage regime	Crop species	Stem elongation	Maturity[z]	Stem elongation	Maturity	Stem elongation	Maturity	Stem elongation	Maturity
Reduced tillage		(kg N ha^{-1})							
	Red clover	28	42*b*	–	–	17	33*e*	23	27*ab*
	Sweet clover	34	60*a*	–	–	28*e*		24	29*a*
	Pea	29	31*bcd*	46	58	18	31*e*	11	16*bcd*
	Hairy vetch	26	29*cd*	36	50	24	27*e*	–	–
	Lentil	23	30*cd*	38	53	17	28*e*	13	14*cd*
	Soybean	25	25*d*	38	46	27	33*e*	11	14*cd*
	Cowpea	23	30*bcd*	38	52	20	28*e*	12	16*cd*
	Oil seed radish	–		32	37	16	28*e*	12	12*d*
	Control	22	26*d*	35	36	18	32*e*	13	15*cd*
Conventional tillage									
	Red clover	26	34*bcd*	–	–	34	38*de*	30	29*a*
	Sweet clover	24	34*bcd*	–	–	35	49*bcd*	31	23*abcd*
	Pea	24	37*bc*	54	80	39	39*cde*	23	22*abcd*
	Hairy vetch	22	32*bcd*	57	91	34	51*bcd*	–	–
	Lentil	26	33*bcd*	48	90	43	66*a*	25	25*abc*
	Soybean	24	30*cd*	48	87	23	49*bcd*	22	26*abc*
	Cowpea	23	32*bcd*	53	79	38	52*abc*	29	29*a*
	Oil seed radish	–	–	52	88		30	27	28*ab*
	Control	26	37*bc*	53	73	36	55*ab*	22	26*abc*
Means									
Reduced tillage		26	34	38*b*	47*b*	19*b*	28*b*	14*b*	17
Conventional tillage		23	33	52*a*	83*a*	35*a*	50*a*	25*a*	25
LSD (tillage regime)		–	–	10.2	36.2	4.2	–	9.8	–
LSD (crop species)		–	–	5.3	–	–	–	4.3	–
Source of variation		*P* values							
	Crop species (CS)	0.0560	0.0038	0.0414	0.5077	0.566	0.2967	<0.0001	0.0783
	Tillage regime (TR)	0.2535	0.789	0.0214	0.0497	0.0012	0.0112	0.0351	0.2152
	CS × TR	0.2373	0.0148	0.0838	0.6872	0.6543	0.0496	0.3229	0.0254
Contrasts									
Relay crops vs. double crops		0.0108	<.0001	–	–	0.9303	0.2756	<.0001	0.0027

[z]Wheat at soft dough.
a–e Experiments with significant crop species × tillage regime interaction means within a column followed by the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level of significance.

productivity is more evident under dry conditions; an observation that did not apply in the present study. As a result of lower temperatures in autumn, late-season seeded cover crops have higher water use efficiencies than spring-seeded crops (Nielsen et al. 2005). Therefore, improved water use efficiency of pea seeded under RT management in spring-seeded situations may not apply in late-season situations.

Relay Crops versus Double Crops

The two most productive late-season cover crop species in this study were red clover and pea. A comparison of the biomass production of these species showed that red clover produced more biomass than RT pea at 4 of 5 site years and red clover produced more biomass than CT pea at 3 of 5 site years (Table 6). Only in 1 of 5 site years did red clover produce less biomass than pea. Therefore, the best relay crop (red clover) produced as much or more biomass as the best double crop (pea) in the majority of the cases. However, unlike red clover, which failed 1 out of 6 yr to produce biomass, pea consistently produced biomass at all 8 site years. Therefore, despite having less biomass, pea established more consistently than red clover. Since red clover is much lower cost to establish ($30 – 60 ha^{-1} at 10 kg ha^{-1} seeding rate) than pea ($80 – 100 ha^{-1} at 100 kg ha^{-1} seeding rate), producers may opt for red clover for economic reasons.

Wheat N Uptake, Yield and Protein Response

In some of the study sites, wheat was used as a test crop to assess the effect of cover crops and tillage regime on N uptake and yield in a following crop. Relay and double crop effects on wheat N uptake at stem elongation and maturity, grain yield and protein concentration were tested. We were particularly interested in determining whether any of the cover crop/tillage regimes provided a yield and N advantage for the following crop over the common practice of leaving the field fallow after winter crop grain harvest.

Wheat N Uptake at Stem Elongation

N uptake at wheat stem elongation stage is an important measure of a system's early-season N-supplying power with implications for yield potential and weed competition (Crews and Peoples 2005). In the present study, cover crop species significantly affected N uptake at 2 of 4 sites (Table 7). At Carman in 2009, wheat after pea, hairy vetch and cowpea accessed more N than for all other cover crops. Red and sweet clover had not established in the previous year at Carman. At Notre DL, wheat after relay-cropped red and sweet clover took up more N than other plots, including pea. Relay crops at Notre DL had produced significantly more biomass than double crops and this appeared to increase early- season N availability to wheat.

Nitrogen benefits of relay-cropped red clover to corn were observed in Michigan and Ontario (Hesterman 1992; Vyn et al. 2000) but lack of red clover N benefit to canola in Alberta (Blackshaw et al. 2010a), on the other hand, resulted from negligible cover crop biomass production (40 to 90 kg ha^{-1}) of the red clover in those semi-arid conditions. One surprising observation in the present study was the inability of very high legume cover crop biomass (3696 kg ha^{-1}) to raise N uptake in wheat at Glenlea in 2008 (Table 7). A possible explanation for the poor N capture may be associated with very wet spring conditions that may have caused denitrification or leaching at this site.

Tillage increased early-season N availability at three of four sites. Wheat at stem elongation in the CT plots took up 7–21 kg ha^{-1} more N than wheat in RT plots (Table 7). This finding shows that delaying tillage until spring reduces early season N availability. Reduced early N availability from no-till legumes has been shown by other workers (Groffman et al. 1987; Varco et al. 1993). A recent Manitoba study (Vaisman et al. 2011) showed that compared with CT, reducing tillage operations in an organic pea–oat green manure resulted in less available N (38 to 50% reduction) to the following wheat crop. These authors also observed that N availability did not increase in spring-tilled treatments compared with no-till treatments and concluded that reducing tillage in organic green manure systems significantly reduces N mineralization.

The absence of significant crop species × tillage regime interactions for early season N uptake in the present study indicates that tillage had the same effect on N mineralization for all cover crops tested.

Wheat N Uptake at Maturity

Nitrogen uptake at crop maturity is a measure of seasonal N-supplying power of the cropping system. In the present study, wheat N uptake at maturity ranged from 12 to 91 kg ha^{-1} (Table 7) and was generally lower than that reported in other Manitoba studies on organic wheat production [e.g., 95 to 205 kg ha^{-1} and 50 to 81 kg ha^{-1} reported by Vaisman et al. (2011) and Wiens et al. (2006), respectively]. It is plausible that the extremely low N uptake at Notre DL (12 to 29 kg ha^{-1}) resulted from immobilization of N by the very high levels of fall rye residue.

The overwhelming outcome at wheat maturity was that the effect of cover crop species on N uptake was strongly modified by tillage regime. Significant species by tillage interactions were observed at 3 of 4 site-years (Table 7). Only at Carman in 2009 was no significant interaction observed. For most site years, the crop species main effect was not significant at maturity, indicating that there was little difference in N-supplying capacity of the different cover crops.

The reasons for significant tillage by cover crop species interactions were different at the different site-years. At Notre DL and Glenlea some cover crops did not produce any biomass (soybean and cowpea). Where no cover crop biomass was produced, reducing tillage usually decreased wheat N uptake (Table 7). Where cover crops successfully produced biomass the previous autumn (pea, lentil, clovers and hairy vetch), reducing tillage either did not affect N uptake or increased N uptake. A possible explanation for the interaction is as follows. Where no legume biomass was produced, reducing tillage immobilized N, a process that is well documented (Mulvaney et al. 2010). However, where cover crop legume biomass was produced, the N immobilization effect of RT appears to have been offset by the added legume N. This suggests that when legume biomass is present, fall tillage may be eliminated without negative effects on wheat N uptake in the following year.

A linear regression analysis was conducted (data not shown) to investigate the relationship between legume biomass production and wheat N uptake at stem elongation and maturity. No consistent pattern among site years, as to how much biomass was required to offset the slow mineralization resulting from absence of tillage was observed. Analyzing the N contribution of relay-cropped red clover to corn Liebman et al. (2012) found inconsistent response of soil nitrate and corn stalk N concentrations to time of tillage (fall and spring tillage). However, they did find a significant positive correlation between corn yield and red clover biomass production. Future research using ^{15}N-labeled cover crops can help in determining the fate of cover crop N after incorporation.

Wheat Grain Yield and Protein

Significant crop species effects for wheat grain yield were observed at Glenlea, Carman 2009 and at Notre DL (Table 8). Since the grain yield potential is largely affected by N availability before anthesis (Demodes-Mainard et al. 1999), early-season N availability provided by legume biomass (as measured in wheat stem elongation N uptake) was reflected in higher yields. For instance, at Carman in 2009, wheat after pea yielded the highest (no red and sweet clover growth at this site year).

The tillage regime effect was significant for wheat yield at 3 of 4 site years, where wheat grown in CT plots yielded more than wheat grown in RT plots. Perhaps,

Table 8. Wheat yield and grain protein following reduced tilled (RT) and conventional tilled (CT) red clover, sweet clover, pea, hairy vetch, lentil, soybean, cowpea, and oil seed radish and control at Carman, Glenlea and Notre Dame de Lourdes (Notre DL) Manitoba in 2009 and 2010

		Yield				Grain protein			
TreatZments		2009		2010		2009		2010	
Tillage regime	Crop species	Glenlea	Carman	Carman	Notre DL	Glenlea	Carman	Carman	Notre DL
Reduced tillage		(kg ha^{-1})				(g N kg^{-1})			
	Red clover	741*ab*	–	749	1595*ab*	135	–	117	121
	Sweet clover	934*a*	–	943	1486*abc*	138	–	111	113
	Pea	543*bcdef*	2118	831	553*g*	137	117	116	116
	Hairy vetch	389*defgh*	1733	870	–	134	111	112	–
	Lentil	300*gh*	1676	677	633*g*	138	117	111	114
	Soybean	336*fgh*	1575	790	500*g*	137	115	115	113
	Cowpea	274*h*	1718	764	517*g*	137	116	113	109
	Oil seed radish	–	1409	670	589*g*	–	114	110	115
	Control	354*efgh*	1593	811	517*g*	132	115	111	110
Conventional tillage									
	Red clover	752*abc*	–	1371	1404*ab*	146	–	120	115
	Sweet clover	662*bc*	–	1362	1561*a*	139	–	121	118
	Pea	571*bcde*	2929	1411	1328*abcd*	142	129	122	115
	Hairy vetch	511*cdefg*	2574	1433	–	141	129	125	–
	Lentil	590*bcd*	2416	1609	1381*abc*	137	126	125	119
	Soybean	506*cdefg*	2602	1389	1072*def*	138	127	122	119
	Cowpea	503*cdefg*	2519	1462	1314*bcd*	138	126	123	115
	Oil seed radish	–	2522	1351	1306*bcd*	–	130	121	115
	Control	671*bc*	2390	1362	1148*cde*	137	125	123	117
Means									
Reduced tillage		484	1688*b*	789*b*	785	135	114*b*	112*b*	113
Conventional tillage		596	2564*a*	1416*a*	1284	139	127*a*	121*a*	115
	LSD (tillage regime)	–	571	197	–	–	11.2	9.1	–
	LSD (crop species)	–	322	–	–	–	–	–	–
Source of variation		*P* values							
	Crop species (CS)	<0.0001	0.0258	0.6353	<0.0001	0.8500	0.9158	0.8372	0.0587
	Tillage regime (TR)	0.0148	0.0165	0.002	0.0876	0.4120	0.0380	0.0442	0.3200
	CS × TR	0.0363	0.8885	0.1229	<0.0001	0.5176	0.7465	0.2463	0.0774
Contrasts									
Relay crops vs. double crops		<0.0001	–	0.9393	<0.0001	0.3086	–	0.7952	0.0732

a–f Experiments with significant crop species × tillage regime interaction means within a column followed by the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level of significance.

the lack of adequate biomass production of double crops at Carman in 2008 and 2009 resulted in poorer N supply to wheat in RT plots than CT plots. There were significant crop species × tillage regime interaction effects for yield at Glenlea and Notre DL (Table 8). At Glenlea, wheat in the CT control and cowpea plots yielded better than RT ones but wheat in all the other crop plots yielded same under both tillage regimes. At Notre DL wheat grown in RT relay crop plots yielded same as CT ones but for double crops wheat yielded better under CT. At Notre DL red and sweet clover biomass production were 2109 and 1259 kg ha^{-1}, while double crop biomass production only reached 570 kg ha^{-1} for CT pea. Thus, once again, the capacity of late-season legume biomass production offsetting the slow N mineralization from RT is illustrated in these wheat yield response results.

Wheat grain protein concentration was not influenced by cover crop species. However, a significant tillage regime effect was observed in Carman 2009 and 2010 where wheat had higher amounts of protein in CT plots than RT plots. Reduced grain protein following reduced or no-till management, compared with conventional tillage, has been shown in other studies (Blackshaw et al. 2010b; Vaisman et al. 2011). There were no significant crop species and tillage interactions for grain protein, indicating that the crop species effect on grain protein was not influenced by tillage regime.

CONCLUSIONS

This experiment has shown that most of the tested relay and double crops can establish successfully under both conventional tillage and direct seeding practices. Under all conditions and site years, lentil successfully established but failed to produce sufficient biomass to provide N benefit to wheat. Red clover, sweet clover and pea were the highest biomass producing crops. Pea managed under RT produced comparable or more biomass than CT pea. Therefore, direct-seeded pea is a better option than CT pea for soil and energy conservation. Biomass production of all legumes fluctuated greatly by year and location. Overall, relay crops were more productive than double crops.

Wheat N uptake and yield increased with increasing relay and double crop biomass production at most site years. Although biomass production and N benefit vary by site and year, low seed cost and seeding rates of red and sweet clovers make them attractive options for low-input organic farmers. Pea is also recommended as it produced acceptable amounts of biomass 6 out of 8 site years. Relay crops in the present experiment appear to provide more N benefit than double crops.

Results of this study provided evidence that adequate biomass production by clovers and pea were effective at offsetting reduced tillage-induced N mineralization reduction. Without the legume N from these cover crops, eliminating fall tillage almost always reduced N supply to the following wheat crop. Therefore, this study provided evidence that the presence of a late-season cover may facilitate reduced tillage in organic farming by offsetting the N limitations that occur when fall tillage is eliminated. Further research is needed to establish the amount of critical cover crop biomass needed to reduce tillage in organic late-season cover crop production.

Berry, P. M., Sylvester-Bradley, R., Philipps, L., Hatch, D. J., Cuttle, S. P., Rayns, F. W. and Gosling, P. 2002. Is the productivity of organic farms restricted by the supply of available nitrogen? Soil use Manage. **18** (Suppl.): 248–255.

Biederbeck, V. O., Bouman, O. T., Looman, J., Slinkard, A. E., Bailey, L. D., Rice, W. A. and Janzen, H. H. 1993. Productivity of four annual legumes as green manure in dryland cropping systems. Agron. J. **85**: 1035–1043.

Blackshaw, R. E., Molnar, L. J. and Moyer, J. R. 2010a. Suitability of legume cover crop-winter wheat intercrops on the semi-arid Canadian prairies. Can. J. Plant Sci. **90**: 479–488.

Blackshaw, R. E., Molnar, L. J. and Moyer, J. R. 2010b. Sweet clover termination effects on weeds, soil water, soil nitrogen, and succeeding wheat yield. Agron. J. **102**: 634–641.

Blaser, B. C., Singer, J. W. and Gibson, L. R. 2011. Winter cereal canopy effect on cereal and interseeded legume productivity. Agron. J. **103**: 1180–1185.

Blaser, B. C., Singer, J. W. and Gibson, L. R. 2007. Winter cereal, seeding rate, and intercrop seeding rate effect on red clover yield and quality RID G-6260-2010. Agron. J. **99**: 723–729.

Borstlap, S. and Entz, M. 1994. Zero-tillage influence on canola, field pea and wheat in a dry subhumid region – agronomic and physiological-responses. Can. J. Plant Sci. **74**: 411–420.

Brandsaeter, L. O., Thomsen, M. G., Waernhus, K. and Fykse, H. 2012. Effects of repeated clover undersowing in spring cereals and stubble treatments in autumn on *Elymus repens, Sonchus arvensis* and *Cirsium arvense*. Crop Prot. **32**: 104–110.

Bremer, E. and Vankessel, C. 1992. Plant-available nitrogen from lentil and wheat residues during a subsequent growing-season. Soil Sci. Soc. Am. J. **56**: 1155–1160.

Carr, P. M., Martin, G. B. and Horsley, R. D. 2009. Impact of tillage on field pea following spring wheat. Can. J. Plant Sci. **89**: 281–288.

Crews, T. and Peoples, M. 2005. Can the synchrony of nitrogen supply and crop demand be improved in legume and fertilizer-based agroecosystems? A review. Nutr. Cycling Agroecosyst. **72**: 101–120.

Demotes-Mainard, S., Jeuffroy, M. H. and Robin, S. 1999. Spike dry matter and nitrogen accumulation before anthesis in wheat as affected by nitrogen fertilizer: Relationship to kernels per spike. Field Crops Res. **64**: 249–259.

Environment Canada. 2013. Canadian climate normals and averages. [Online] Available: http://www.climate.weatheroffice.gc.ca/climate_normals/index_e.html. [2013 Mar. 20].

Groffman, P. M., Hendrix, P. F. and Crossley Jr., D. A. 1987. Nitrogen dynamics in conventional and no-tillage agroecosystems with inorganic fertilizer or legume nitrogen inputs. Plant Soil **97**: 315–332.

Hartl, W. 1989. Influence of undersown clovers on weeds and on the yield of winter-wheat in organic farming. Agric. Ecosyst. Environ. **27**: 389–396.

Hesterman, O., Griffin, T., Williams, P., Harris, G. and Christenson, D. 1992. Forage-legume small-grain intercrops - nitrogen-production and response of subsequent corn. J. Prod. Agric. **5**: 340–348.

Krauss, M., Berner, A., Burger, D., Wiemken, A., Niggli, U. and Maeder, P. 2010. Reduced tillage in temperate organic farming: Implications for crop management and forage production. Soil Use Manage. **26**: 12–20.

Liebman, M., Graef, R. L., Nettleton, D. and Cambardella, C. A. 2012. Use of legume green manures as nitrogen sources for corn production. Renew. Agric. Food Syst. **27**: 180–191.

Maynard, D. G., Kalra, Y. P. and Crumbaugh, J. A. 2007. Nitrate and exchangeable ammonium nitrogen. Pages 71 to 80 *in* M. R. Carter and E. G. Gregorich, eds. Soil sampling and methods of analysis. 2nd ed. CRC Press, Boca Raton, FL.

Mulvaney, M. J., Wood, C. W., Balkcom, K. S., Shannon, D. A. and Kemble, J. M. 2010. Carbon and nitrogen mineralization and persistence of organic residues under conservation and conventional tillage. Agron. J. **102**: 1425–1433.

Nadler, A. J. and Bullock, P. R. 2011. Long-term changes in heat and moisture related to corn production on the canadian prairies. Clim. Change **104**: 339–352.

Nielsen, D., Unger, P. and Miller, P. 2005. Efficient water use in dryland cropping systems in the great plains. Agron. J. **97**: 364–372.

Peigné, J., Ball, B. C., Roger-Estrade, J. and David, C. 2007. Is conservation tillage suitable for organic farming? A review. Soil Use Manage. **23**: 129–144.

Peoples, M., Bowman, A., Gault, R., Herridge, D., McCallum, M., McCormick, K., Norton, R., Rochester, I., Scammell, G. and Schwenke, G. 2001. Factors regulating the contributions of fixed nitrogen by pasture and crop legumes to different farming systems of eastern Australia. Plant Soil **228**: 29–41.

Plaza, A. 2011. Soil mineral nitrogen content after undersown crops in autumn and spring in the conventional and organic farming system. Fresenius Environ. Bull. **20**: 2446–2450.

Queen, A., Earl, H. and Deen, W. 2009. Light and moisture competition effects on biomass of red clover underseeded to winter wheat. Agron. J. **101**: 1511–1521.

SAS Institute, Inc. 1985. SAS procedures guide for personal computers. Version 12 ed. SAS Institute, Inc., Cary, NC.

Schipanski, M. E. and Drinkwater, L. E. 2011. Nitrogen fixation of red clover interseeded with winter cereals across a management-induced fertility gradient. Nutr. Cycl. Agroecosyst. **90**: 105–119.

Singer, J., Casler, M. and Kohler, K. 2006. Wheat effect on frost-seeded red clover cultivar establishment and yield RID G-6260-2010. Agron. J. **98**: 265–269.

Sjursen, H., Brandsaeter, L. O. and Netland, J. 2012. Effects of repeated clover undersowing, green manure ley and weed harrowing on weeds and yields in organic cereals. Acta Agric. Scand. Sect. B Soil Plant Sci. **62**: 138–150.

Soon, Y. K., Clayton, G. W. and Rice, W. A. 2001. Tillage and previous crop effects on dynamics of nitrogen in a wheat-soil system. Agron. J. **93**: 842–849.

Statistics Canada 2013. Field crop reporting series. [Online] Available: http://www5.statcan.gc.ca/bsolc/olc-cel/olc-cel?lang=eng&catno=22-002-XIB [2013 Mar. 31].

Thiessen Martens, J. R. and Entz, M. H. 2001. Availability of late-season heat and water resources for relay and double cropping with winter wheat in prairie Canada. Can. J. Plant Sci. **81**: 273–276.

Thiessen Martens, J. R., Hoeppner, J. W. and Entz, M. H. 2001. Legume cover crops with winter cereals in southern Manitoba: Establishment, productivity, and microclimate effects. Agron. J. **93**: 1086–1096.

Vaisman, I., Entz, M. H., Flaten, D. N. and Gulden, R. H. 2011. Blade roller-green manure interactions on nitrogen dynamics, weeds, and organic wheat. Agron. J. **103**: 879–889.

Varco, J., Frye, W., Smith, M. and Mackown, C. 1993. Tillage effects on legume decomposition and transformation of legume and fertilizer N-15. Soil Sci. Soc. Am. J. **57**: 750–756.

Vyn, T., Faber, J., Janovicek, K. and Beauchamp, E. 2000. Cover crop effects on nitrogen availability to corn following wheat. Agron. J. **92**: 915–924.

Vyn, T. J., Janovicek, K. J., Miller, M. H. and Beauchamp, E. G. 1999. Soil nitrate accumulation and corn response to preceding small-grain fertilization and cover crops. Agron. J. **91**: 17–24.

Wiens, M. J., Entz, M. H., Martin, R. C. and Hammermeister, A. M. 2006. Agronomic benefits of alfalfa mulch applied to organically managed spring wheat. Can. J. Plant Sci. **86**: 121–131.

Williams, S. and Weil, R. 2004. Crop cover root channels may alleviate soil compaction effects on soybean crop. Soil Sci. Soc. Am. J. **68**: 1403–1409.

Zentner, R. P., Campbell, C. A., Biederbeck, V. O., Selles, F., Lemke, R., Jefferson, P. G. and Gan, Y. 2004. Long-term assessment of management of an annual legume green manure crop for fallow replacement in the brown soil zone. Can. J. Plant Sci. **84**: 11–22.