The Benefits of Legume Crops on Corn and Wheat Yield, Nitrogen Nutrition, and Soil Properties Improvement

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ABSTRACT

Legume crops leave N-rich residues and improve soil properties that can boost the yield of subsequent crops. This study conducted at two sites in Québec, eastern Canada, identified the most appropriate preceding legume crops for subsequent corn (*Zea mays* L.) and wheat (*Triticum aestivum* L.) yield and N nutrition. Legumes were established in 2011, in monoculture or mixed with grain crops, for a total of 13 treatments: common bean (*Phaseolus vulgaris* L.), soybean (*Glycine max* L.), dry pea (*Pisum sativum* L.), hairy vetch (*Vicia villosa* Roth), alfalfa (*Medicago sativa* L.), and crimson clover (*Trifolium incarnatum* L.), hairy vetch/wheat, crimson clover/wheat, field pea/wheat, alfalfa/corn, hairy vetch/corn, crimson clover/corn) and a non-N fixing crop (corn) as the control. In 2012, each plot was split and five N fertilizer rates applied to corn and wheat. Four legume systems (alfalfa, hairy vetch, crimson clover, and hairy vetch/wheat) significantly increased the soil structure stability, alkaline phosphatase and dehydrogenase activities at warmer St-Mathieu-de-Beloeil location but not at the cooler St-Lambert-de-Lauzon site. These legumes also significantly increased yields and N nutrition of corn and wheat at St Mathieu-de-Beloeil and of wheat only at St-Lambert-de-Lauzon. Although legume N credit was found low (~30 kg N ha^{-1}), the N fertilizer replacement value was 51 to 77 kg N ha^{-1} for corn and up to 37 kg N ha^{-1} for wheat, depending on the preceding legume crop. This suggests that indirect effects related to improved soil properties impacted positively corn and wheat yield and N nutrition.

Nitrogen is the most limiting nutrient and the most expensive fertilizer in cereal production. Enhanced crop yields are often associated with increasing N fertilizers, which may lead to low N use efficiency and environmental concerns due to N losses to waterways and to the atmosphere. Reducing required N fertilizer inputs can be achieved by including legumes into crop rotations (Peoples et al., 1995). Legume crops improve grain yield considerably and can replace entirely or partially the N fertilizer required by cereals (McVay et al., 1989; Peoples et al., 1995; Hardarson and Atkins, 2003; N'Dayegamiye et al., 2012). This may result in reducing the use of expensive synthetic N fertilizer and enhancing soil fertility (Hesterman et al., 1987; Hardarson and Atkins, 2003) and thus generate considerable economic and environmental benefits (Pimentel et al., 2005).

Besides their N contribution, benefits of legumes on subsequent crops are related to other factors, referred to as "rotation effects" (Maloney et al., 1999). These factors include improvement in water use efficiency, soil moisture and nutrient availability, soil structure and microbial activity, reduction in weeds, and breaking the cycles of insects and disease, and phytotoxic and allelopathic effects (Baldock et al., 1981; Hesterman, 1988).

Nitrogen contribution by legumes to the succeeding crops lies in the legume's ability to fix atmospheric N_2 through the legume-*Rhizobium* symbiosis (Peoples and Craswell, 1992). Some legumes such as alfalfa, hairy vetch, and crimson clover are considered strong N_2–fixers since they can derive 50 to 90% of their total N requirements from symbiotic nitrogen fixation (Hesterman, 1988; McVay et al., 1989; Griffin et al., 2000). Conversely, other legumes such as common bean are considered rather poor N_2–fixers and thus, require supplemental N fertilization to achieve maximum grain yields (Peoples and Craswell, 1992). For each legume crop, the rate of N_2 fixation is directly related to plant growth rate. Thereby, the net return of symbiotically fixed N_2 to soil may reflect the soil (texture, pH, nutrients) and climate (temperature, moisture) effects on the ability of legume plants to grow and fix N_2 (Kirda et al., 1989; Evans et al., 1991; Hesterman et al., 1992; O'Hara, 2001).

Symbiotically fixed N_2 is available to subsequent crops through mineralization of their residues. Therefore, soil N supply by legumes depends on legume biomass returned to the soil and its mineralization rate (Heichel, 1987). The latter

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Abbreviations: ANE, agronomic nitrogen efficiency; CHU, corn heat units; MWD, mean weight diameter of aggregates; PPNT, preplant nitrate test; PSNT, pre-sidedress nitrate test.

is determined by the biochemical composition of the legume biomass, particularly C/N ratio, polyphenol, lignin, and N contents (Melillo et al., 1989; Fox et al., 1990), soil and climate conditions (Myers et al., 1982). Synchronization between the amount and timing of legume N release with subsequent crop N demand remains a serious challenge for efficient utilization of legume N by the following grain crop (Cherr et al., 2006). In temperate regions, mineral N release from crop residues is slow in winter and early spring when soils are cool and is more rapid in summer as soils warm up (Heckman, 2002). Thereby, a long growing-season crop may accumulate more N released from previous legume residues compared to short-season crops (Varvel and Wilhelm, 2003).

In temperate regions of North America, the dominant corn–wheat–soybean rotation can be diversified by introducing cash crops (pea, dry bean) in the rotation crops (Walley et al., 2007). Legumes such as alfalfa, hairy vetch, and crimson clover can be grown to extend the crop rotations as they produce high dry matter and are considered strong N_2–fixers (Hesterman, 1988; McVay et al., 1989; Griffin et al., 2000). Another option is to intercrop these forage legumes with corn to improve soil fertility through N_2 fixation and reduce diseases, weeds, and soil erosion (Hauggaard-Nielsen et al., 2003). Intercropping forage legumes with small grains also is an effective practice to increase forage yield and quality, and to increase soil N status (Biederbeck et al., 1995; Carr et al., 2004). Still, the N inputs and other soil improvements derived from these legume crops vary widely in response to differences in soil and climatic conditions (Biederbeck et al.1995; Carr et al., 2004; Dhima et al., 2007), and thus choosing the best way to integrate legumes into a legume–cereal rotation is still challenging.

This study was undertaken to identify the most appropriate legume crop before corn and wheat production in the cool humid climate of Québec, eastern Canada. The objectives were to: (i) compare the efficiency of grain legumes (soybean, pea, dry bean), legumes (crimson clover, alfalfa, hairy vetch) in monoculture or intercropped with a cereal (corn or wheat) to accumulate N under different soil and climatic conditions of Québec; (ii) evaluate the effects of the different legume crops on yield, N uptake, and agronomic N efficiency of subsequent corn and wheat; (iii) determine the optimal N fertilizer rate required to reach maximum corn and wheat yields and (iv) assess the effects of legume residues incorporation on soil N availability, soil aggregation and aggregate stability, and microbial activity.

MATERIALS AND METHODS

Site Description and Experimental Design

A 2-yr study was performed in two fields located in two different agro-climatic regions of Québec, eastern Canada. The first field was located at St-Mathieu-de-Beloeil (46°35′00″ N and 71°12′00″ W) in central Québec. The soil was a clay loam of the St-Urbain series (sandy over clayey, mixed, non-acid, frigid, Typic Humaquept). The particle-size distribution of the A horizon (0–20 cm) was 240 g kg^{-1} sand, 270 g kg^{-1} silt, and 490 g kg^{-1} clay. Initial soil pH value (1:1 soil/water) was 7.2 and the soil C and N contents were 45.9 g kg^{-1} C and 2.1 g kg^{-1} N, respectively.· Soil available nutrient concentrations were 44.50 mg P kg^{-1}, 373.0 mg K kg^{-1}, 3293 mg Ca kg^{-1}, and 800 mg Mg kg^{-1}.

The second field was located at St-Lambert-de-Lauzon (45°55′82″ N and 73°19′90’″ W) in Chaudières-Appalaches in eastern Québec. The soil was a clay loam of the Le Bras series (sandy over clayey, mixed, non-acid, frigid, Typic Humaquept). The particle-size distribution of the A horizon (0–20 cm) was 320 g kg^{-1}sand, 430 g kg^{-1}silt, and 260 g kg^{-1}clay. The initial soil pH (1:1 soil/water) was 6.4 and the soil total C and N contents were 34.8 g C $kg^{-1}$and 1.6 g N kg^{-1}, respectively. Soil available nutrient concentrations were 26.40 mg P kg^{-1}, 65.5 mg K kg^{-1}, 1004.0 mg Ca kg^{-1}, and 897 Mg kg^{-1}.

Average monthly temperature and precipitation were comparable at the two sites in 2011 (Table 1). In 2012, the growing season was colder and higher precipitation was recorded at St-Lambert-de-Lauzon than St-Mathieu-de-Beloeil.

Field experiments were initiated at both sites in 2011, laid out in a complete randomized block design with three replications. Each block was divided in 13 experimental units of 50 by 6 m, and treatments consisted in 13 cropping systems: six legumes grown under monocultures: three grain legumes (common bean, soybean, and dry pea), three legumes (hairy vetch, alfalfa, and crimson clover), three legumes in association with wheat (hairy vetch/wheat, crimson clover/wheat, and field pea/wheat), three legumes in row intercrop with corn (alfalfa/corn, hairy vetch/corn, and crimson clover/corn) and corn as a non-N_2 fixing crop reference for evaluation of the legume N contribution.

At both locations, crops were seeded at the end of May. Corn hybrids used in the experiments were Dekalb-343-2550 corn heat units (CHU) at St-Lambert-de-Lauzon and Dekalb-4710-2950 CHU at St-Mathieu-de-Beloeil, and were seeded at 80,000 plants ha^{-1}. Wheat (variety Nass) mixed with legumes was seeded at 130 kg ha^{-1}. Soybean (variety Inverness) was seeded at 128 kg ha^{-1} and dry pea (variety CDC Meadow) and common bean (Envoy type Navy) at 220 kg ha^{-1} and 108 kg ha^{-1}, respectively. Crimson clover, alfalfa and hairy vetch were seeded at 15 kg ha^{-1}, 24 kg ha^{-1}, and 48 kg ha^{-1}, respectively.

Nitrogen fertilizer rate for legume crops cultivated alone was fixed at 30 kg N ha^{-1} and no N fertilizer was applied for different legume crops intercropped or mixed with wheat or corn. Nitrogen fertilizer was applied at a rate of 170 kg N ha^{-1} for corn and 90 kg N ha^{-1} for wheat. Phosphorus and K were applied on all plots as triple superphosphate at a rate of 50 kg P_2O_5 ha^{-1}, and K at a rate of 75 kg K_2O ha^{-1} as KCl.

For grain legume crops (common bean, soybean, and pea), grain and residue yields were determined at harvest in August 2011. For legumes associated with wheat (vetch and pea), vegetative biomass was harvested in August at wheat milk stage. For wheat–clover treatment, wheat was harvested at maturity while clover grew until the beginning of October. For clover, alfalfa, and vetch seeded alone, total aboveground biomass was harvested at the end of September in both locations. After each crop harvest, organic residues or legume biomass were harvested from the plot surface and then incorporated into the soil by disc harrowing to a depth of 10 cm. Corn was harvested in late October, and intercropped legumes were harvested in the two middle rows, weighed, and spread uniformly on the soil surface. All plots were tilled to a depth of 15 cm in November. At each crop harvest, organic residues and vegetative biomass were sampled to determine dry matter and N content.

In 2012, each experimental unit was divided in two plots (25 by 6 m) for wheat and corn as succeeding crops. Each previous crop plot was divided in five subplots (5 by 6 m) to which five N fertilizer rates were randomly assigned: 0, 20,

Table 1. Cumulative temperature and rainfall during the cropping season in 2011 and 2012 at St-Lambert-de-Lauzon and St-Mathieu-de-Beloeil locations (Québec, Canada).

	St-Lambert-de-Lauzon		St- Mathieu-de-Beloeil	
Months	2011	2012	2011	2012
		Temperature, °C		
May	9.4	9.4	12.3	14.8
June	16.4	13.6	15.8	19.3
July	18.2	17.3	20.4	21.2
August	17.3	15.2	18.2	17.9
September	12.8	12.3	13.6	14.7
		Rainfall, mm		
May	59.4	97.5	97.5	92.3
June	180.9	76.2	176.2	52.3
July	167.7	51.9	151.9	44.2
August	106.1	110.5	140.5	91.8
September	103.4	88.8	88.8	80.8

40, 60, and 80 kg N ha^{-1} for wheat, and 0, 50, 100, 150, and 200 kg N ha^{-1} for corn. The experimental design was a split-plot with previous cropping systems in main plots, and N fertilizer rates in subplots. Each corn subplot was 5 m long and 6 m wide, and consisted of eight rows with 0.75- m row spacing. Nitrogen fertilizer was applied as calcium ammonium nitrate (27%) and was split-applied for corn: the first 50 N kg ha^{-1} as a starter and the remaining fraction at the six leaf (V6) corn growth stage. Phosphorus and K fertilizers were applied at planting rates of 50 kg P_2O_5 ha^{-1} and 75 kg K_2O ha^{-1} as triple superphosphate and KCl, respectively. Corn hybrids used in the experiments were Dekalb-343-2550 CHU at St-Lambert-de-Lauzon and Dekalb-4710-2950 CHU at St-Mathieu-de-Beloeil, and were seeded at 81,000 plants ha^{-1}.

For wheat, N fertilizer was applied at pre-seeding as calcium ammonium nitrate (27%). Phosphorus was applied as triple superphosphate at a rate of 50 kg P_2O_5 ha^{-1}, and K at a rate of 75 kg K_2O ha^{-1} as KCl. Wheat (variety Nass) was seeded at 160 kg ha^{-1}.

Soil Sampling and Analysis

Soil samples were taken in spring 2011 at 20-cm depth before the fertilizer application. In each plot, 10 soil cores were taken randomly with a 2- cm diam. stainless auger (Oakfield model B, Oakfield Apparatus Co., Oakfield, WI), bulked to make a composite sample, air-dried, and sieved to pass a 2-mm sieve. A portion was kept to determine the soil pH, soil texture, and soil nitrate concentrations. Another portion was ground to pass a 0.25-mm sieve for organic C and total N analysis. Soil pH was measured in 1:1 soil/water solution. Soil texture was analyzed using the pipette method after the destruction of soil organic matter with H_2O_2 and dispersion with sodium hexametaphosphate (Gee and Bauder, 1986). Soil nitrate concentrations were determined following extraction with 2 M KCl solution (Bremner, 1965). Extractable P, K, Ca, and Mg were determined in a Mehlich III solution (Mehlich, 1984) and measured on inductively coupled plasma optical emission spectrometer (PerkinElmer 4300 DV, Boston, MA). The soil C and N contents were determined by dry combustion using an automated analyzer (Leco C-N 1000, LECO, St. Joseph, MI).

In 2012, soil samples (0–30-cm depth) were collected only in the check plots (0 kg N ha^{-1}) of each corn or wheat treatment where legumes grew in the previous year. For soil nitrates contents at pre-seeding (PPNT), 10 soil cores were taken from each plot and pooled to make one composite soil sample, air dried and sieved to pass a 2- mm sieve. At the six leaf (V6) corn growth stage, 10 soil cores were again taken from each plot and pooled to make one composite soil sample, sieved to pass a 2- mm sieve and then stored at 4°C until analysis. A portion of the moist soil samples was used to determine soil alkaline phosphatase and dehydrogenase activities. Another portion of the samples was air dried to determine soil nitrate concentration at postseeding (PSNT). Soil nitrates at PPNT and PSNT were extracted with 2 M KCl solution (Bremner, 1965). Dehydrogenase activity was determined by colorimetric measurement of triphenyltetrazolium formazan (TPF) produced by the reduction of 2, 3, 5-triphenyltetrazolium chloride (TTC) according to the method of Casida et al. (1964). Alcaline phosphatase activity was determined by colorimetric measurement of the *p*-nitrophenol released when 1 g of soil was incubated with 4 mL of buffered (pH 11) sodium *p*-nitrophenyl phosphate solution, 0.2 mL of toluene and 1 mL of p-nitrophenol phosphatase at 37°C for 1 h (Tabatabai, 1994).

Three intact soil blocks of about 600 g were removed from each plot with a spade to a depth of 0 to 20 cm, taking care to avoid soil compression, to assess water stable aggregates. Soil blocks were sieved at 8 mm in the field and kept at 4°C until analysis. Water-stable macroaggregates were determined by the wet-sieving method. Forty grams of sieved soil was put on top of a series of sieves (5, 2, 1, and 0.25 mm), which were immersed in water and shaken for 10 min. The soil fractions recovered on each sieve were dried at 65°C for 24 h, corrected for sand and expressed as a percentage of total dry soil (Kemper and Rosenau, 1986). Aggregate mean weight diameter (MWD) was calculated according to Haynes and Beare (1997).

Crop Yield, Nitrogen Uptake, and Agronomic Nitrogen Efficiency

The grain (grain corn, wheat) and biomass yields (corn silage and wheat straw) were measured at the harvest of each crop. Corn grain yields were determined by harvesting the two center rows from each plot. Corn stalks were cut at the soil surface, chopped, and weighed. Wheat grain yields were determined by harvesting a surface of 1.5 by 9 m in the center of each plot with a combine, then wheat straw was collected from the same surface area and weighed. A 600- to 800- g of corn and wheat grain or organic residues subsample was dried at 65°C to determine the dry matter yield and N contents. The N concentration of grain and biomass residues for corn and wheat were determined by dry combustion using a Leco C-N 1000 analyzer. Wheat and corn uptake (kg N ha^{-1}) in the whole plant (biomass and grain) was then summed after multiplying the N concentration and dry matter of each component.

For each previous crop, the agronomic nitrogen efficiency (ANE) for corn and wheat was determined as described by Wortmann et al. (2011):

$$\text{ANE (kg grain kg}^{-1}\text{ N)} = \text{(yield for N fertilized plots} - \text{yield for unfertilized plots)/N fertilizer rate.}$$

Statistical Analysis

Data were analyzed separately for each experimental site and crop and analysis of variance performed using PROC MIXED of SAS (version 9.2, SAS Institute, 2003). The statistical model includes the fixed effects of previous crop, N rates, and previous crops × N fertilizer rates interactions. Type III F tests were performed for the fixed factors and contrasts between crop groups were investigated when the crop effect was found significant at the 0.05 probability level. Different crop groups were created and compared: grain legume crops (2, 3, 4), legumes alone cropped for biomass production (5, 6, 7), legumes with wheat mixture (8, 9, 10), and three legumes intercropped with corn (11, 12, 13). A priori contrasts were used to compare treatment means. When the N rate effect was significant ($P < 0.05$), orthogonal polynomial contrasts were performed to assess if the effect was linear or quadratic.

One-way ANOVA was used to compare the effect of legume crops on soil properties, based on the legume groups defined above. Mixed procedure of SAS was used to conduct statistical analysis with legume groups as fixed effects and blocks as random effects. Crop groups were compared using contrasts when treatments were significant at $P < 0.05$ probability level.

Regression coefficients were computed between corn or wheat yields and N fertilizer rates using the PROC REG of SAS (SAS Institute, 2003). For each previous crop, corn and wheat yields response to N fertilizer rates were fitted with three different models (linear, quadratic, and quadratic-plus-plateau) described by Cerrato and Blackmer (1990). The best regression model was chosen by comparing R-square, lack of fit F tests (Cerrato and Blackmer, 1990) and residual sum of squares. Its adequacy was also checked with residual plots. The following equations Eq. [1] and [2] were used to calculate the N fertilizer rate required to reach maximum corn or wheat yield (Y max).

$$Y = a + bx + cx^2 \text{ if } x < C \qquad [1]$$

and

$$Y = P \text{ if } x > C \qquad [2]$$

where Y is the corn or wheat grain yield (kg ha^{-1}), a is the intercept, b is the linear coefficient, c is the quadratic coefficient and x is the N fertilizer rate (kg N ha^{-1}), C is the critical rate of N fertilization (kg N ha^{-1}) that occurs at the intersection of the quadratic response and the plateau lines, and P represents the plateau yield (kg ha^{-1}).The optimal maximum N rate (N max) and Y max were computed by setting the first derivative of the response equations to zero and then solving for x.

RESULTS AND DISCUSSION

Quantities of Biomass and Nitrogen Incorporated in Soil from Different Previous Crops

At St-Mathieu-de-Beloeil, the amounts of aboveground biomass and N returned to the soil ranged from 0.7 to 5.8 t dry matter ha^{-1}, and from 8 to 134 kg N ha^{-1}, respectively (Table 2). At St-Lambert-de-Lauzon, the amounts of aboveground biomass and N returned to the soil varied between 0.2 and 5.9 Mg dry matter ha^{-1}, and between 5 and 108 kg N ha^{-1}, respectively (Table 3). For both locations, amounts of dry matter incorporated into the soil were highest in the following order: legumes mixed with wheat > legumes in monoculture > grain legumes and legumes intercropped with corn (Tables 2 and 3). The amounts of N returned to the soil were not proportional to dry matter yield and varied widely among legume crops. High N accumulation (> 50 kg ha^{-1}) was observed at both locations for legume in monocultures (hairy vetch,

Table 2. Dry matter (DM) and the C, N, and C/N ratio of crop residues from legumes grown in monoculture or in mixtures with corn or wheat at St-Mathieu-de- Beloeil (Québec, Canada) in 2011.

Crops†	DM	C	C	N	N	C/N
	Mg ha^{-1}	g kg^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}	
1. Dry bean	0.6	404	239	13.2	7.8	31
2. Soybean	2.9	418	1217	8.1	23.2	52
3. Alfalfa	4.4	429	1898	30.4	134.0	14
4. Crimson clover	2.6	420	1092	22.9	59.8	18
5. Hairy vetch	2.8	432	1202	21.4	58.8	20
6. Field pea/wheat	3.9	430	1677	4.8	19.5	86
7. Crimson clover/wheat	3.0	420	1260	5.6	15.0	84
8. Hairy vetch/wheat	5.8	433	2494	21.6	121.8	20
9. Alfalfa/corn	1.2	430	516	23.0	27.8	18
10. Crimson clover/corn	0.7	414	287	18.9	13.3	21
11. Hairy vetch/corn	2.5	442	1100	26.7	67.5	16
			Analysis of variance (*P* value)			
Crop effect	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Contrasts						
1,2 vs. 3,4,5	<0.0001	0.0017	0.0051	<0.0001	<0.0001	<0.0001
1,2 vs. 6,7,8	<0.0001	0.0578	0.0465	<0.0001	<0.0001	ns‡
1,2, vs. 9,10,11	ns	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
3,4,5 vs. 6,7,8	ns	ns	ns	ns	ns	<0.0001
3,4,5 vs. 9,10,11	<0.0001	ns	ns	ns	ns	ns
6,7,8 vs. 9,10,11	<0.0001	0.0472	0.0523	ns	ns	<0.0001

† Dry pea not determined.

‡ ns, not significant.

crimson clover, and alfalfa) and for hairy vetch/wheat. Grain legumes (dry bean, soybean, and dry pea) returned less N to the soil than legumes in monoculture, and legumes intercropped with wheat (Tables 2 and 3), in part because most of N_2 fixed was removed from soil with grain harvest. This is consistent with the removal of 45 to 75% of the N_2 fixed in the aboveground biomass of grain legumes reported by Peoples and Craswell (1992). In contrast, Shipley et al. (1992) have found that hairy vetch retained approximately 90% of the N_2 fixed in aboveground biomass, while 80% of N_2 fixed was in the aboveground biomass of crimson clover.

Legumes intercropped with corn accumulated at least five times less N than those in other legume systems (Tables 2 and 3). Similarly, Kessel and Hartley (2000) reported lower total amounts of N fixed per unit area in intercropping than in monoculture systems. The low performance of legume species in intercropping systems was related to several factors including plant species, seeding ratios, and competition for light and nutrients with the non-legume crop (Roberts et al., 1989; Kessel and Hartley, 2000). Our data suggest that legumes were subjected to greater competition when grown with corn than with wheat.

Corn stalk yields were 4.3 and 3.8 Mg ha^{-1} for corn in monoculture (the control) and corn intercropped with legumes, respectively (data not presented).The N concentrations of corn stalk were low (6.5 g N kg^{-1}) and their N input in the soil varied from 18 to 21 kg N ha^{-1}.

The C/N ratios of organic residues and vegetative biomass varied from 12 to 86 (Tables 2 and 3) and they were lower (<30) for legumes cropped alone or intercropped with corn. Grain legumes and legumes mixed with wheat had the highest C/N ratios (56:90). These results indicate that the decomposition rate is expected to be higher for mono-cropped legumes than for legumes mixed with wheat or grain legumes, which have high C/N ratios and high lignin contents and decompose slowly in soil (Mellilo et al., 1989). The C/N ratio of corn stalk was 88, suggesting that these organic residues with high C/N ratios may decompose slowly in soil and therefore reduces N supply for the subsequent crop.

Effect of Previous Legume Crops on Soil Properties

Soil Microbial Activities

Previous legume crops exerted no significant effect on phosphatase and dehydrogenase activities at St-Lambert-de-Lauzon, whereas they significantly increased alkaline phosphatase (*P* < 0.01) and dehydrogenase (*P*< 0.05) activities at St-Mathieu-de-Beloeil (Tables 4 and 5). Contrast analysis (Table 4; legume group 4, 5, and 6 vs. legume group 7, 8, and 9) showed that dehydrogenase activity was highest in soils with legumes cropped alone or mixed with wheat, while grain legumes and legumes intercropped with corn did not increase this enzyme activity compared with the control without legume (Table 4; 1 vs. legume group 2, 3, and 4; 1 vs. legume groups 11, 12, and 13). Contrast analysis also showed that legumes in monoculture (5, 6, 7) induced higher soil alkaline phosphatase activity than grain legumes or legumes intercropped with wheat or corn (Table 4; legume groups 5, 6, and 7 vs. legume groups 2, 3, and 4; vs. legume groups 8, 9, and 10; vs. legume groups 11, 12, and 13). The greatest increase in dehydrogenase and alkaline phosphatase activities was recorded for hairy vetch, and hairy vetch/wheat followed by alfalfa and crimson clover which had highest dry matter and C and N input (Tables 2 and 3). Our results are in agreement with previous findings by Lovell and Jarvis (1998) and Biederbeck et al. (2005). For example, Biederbeck et al. (2005) reported that legume green manures improved considerably bacterial (385%), fungal populations (210%), and enzyme activities

Table 3. Dry matter (DM) and the C, N, and C/N ratio of crop residues from legumes grown in monoculture or in mixtures with corn or wheat at St-Lambert-de-Lauzon (Québec, Canada) in 2011.

Crops	DM	C	C	N	N	C/N
	Mg ha^{-1}	g kg^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}	
1. Dry pea	2.9	430	1247	14	40.6	30
2. Dry bean	1.4	421	588	6	8.4	70
3. Soybean	2.0	424	840	5	10.0	84
4. Alfalfa	1.8	427	774	28	50.4	15
5. Crimson clover	3.7	422	1554	16	59.2	26
6. Hairy vetch	3.5	433	1505	31	108.5	14
7. Field pea/wheat	5.9	417	2478	6	35.4	70
8. Crimson clover/wheat	2.9	439	1276	8	23.2	55
9. Hairy vetch/wheat	5.9	421	2478	18	106.2	23
10. Alfalfa/corn	0.2	413	782	24	4.8	17
11. Crimson clover/corn	0.5	412	205	17	8.5	24
12. Hairy vetch/corn	0.4	401	160	34	14	12
			Analysis of variance (*P* value)			
Crop effect	<0.0001	0.0069	0.0054	<0.0001	<0.0001	<0.0001
Contrasts						
1,2,3 vs. 4,5,6	ns†	ns	ns	<0.0001	<0.0001	<0.0001
1,2,3 vs. 7,8,9	<0.0001	ns	ns	0.0053	0.0018	<0.0001
1,2,3, vs. 10,11,12	0.0030	0.0009	0.0079	<0.0001	<0.0001	<0.0001
4,5,6 vs. 7,8,9	0.0013	ns	ns	<0.0001	<0.0001	0.0031
4,5,6 vs. 10,11,12	<0.0001	0.0005	0.0016	ns	ns	ns
7,8,9 vs. 10,11,12	<0.0001	0.0010	0.0053	<0.0001	<0.0001	0.0025

† ns, not significant.

Table 4. Effects of preceding crops on pre-plant soil nitrate (PPNT), pre-sidedress nitrate (PSNT), alkaline phosphatase, and dehydrogenase at St-Mathieu-de-Beloeil (Québec, Canada) during the 2012 cropping season.

Preceding crops	PPNT (0–30 cm)	PSNT (0–30 cm)	Alkaline Phosphatase	Dehydrogenase
	——— mg NO_3^-–N kg^{-1}	———	mmol PNP† g^{-1} soil h^{-1}	mmol TPF g^{-1} soil h^{-1}
1. Corn (control)	5.97	4.94	367	119
2. Dry pea	6.07	5.71	373	131
3. Dry bean	5.79	5.22	402	115
4. Soybean	7.02	5.72	409	95
5. Alfalfa	7.94	6.16	459	139
6. Hairy vetch	9.14	6.39	470	146
7. Crimson clover	6.15	5.92	441	141
8. Crimson clover/wheat	5.76	5.95	367	110
9. Field pea/wheat	5.28	5.89	359	196
10. Hairy vetch/wheat	16.25	6.79	465	157
11. Crimson clover/corn	5.69	4.30	375	119
12. Alfalfa/corn	5.87	3.81	384	111
13. Hairy vetch/corn	9.35	5.07	419	121
		Analysis of variance (*P* value)		
Preceding crop effect	ns‡	0.0468	0.0051	0.0417
Contrasts				
1 vs. others	ns	0.0047	0.0498	0.0313
1 vs. 2, 3, and 4	ns	ns	0.0236	ns
1 vs. 5,6 and 7	ns	0.0027	0.0019	0.0383
1 vs. 8, 9 and10	ns	0.0487	ns	0.0428
1 vs. 11, 12, and 13	ns	ns	ns	ns
2, 3, and 4 vs. 5, 6, and 7	ns	0.0259	ns	0.0312
5, 6, and 7 vs. 8, 9, and 10	ns	ns	0.0158	ns
5, 6, and 7 vs. 11, 12, and 13	ns	0.0389	0.0245	0.0328
8, 9, and 10 vs. 11, 12, and 13	ns	0.0018	ns	0.0512

† PNP, *p*-nitrophenol; TPF, triphenyltetrazolium formazan.

‡ ns, not significant.

such as dehydrogenase (202%), phosphatase (171%), and arylsulfatase (287%), compared to a non-N_2–fixing crop. Enhanced microbial activities support greater nutrient mineralization and overall improvement of soil fertility (Kucey et al., 1989). Since dehydrogenase and alkaline phosphatase are present in all microorganisms and is linked to viable cells, our results indicate that most of the monocropped legumes (hairy vetch, crimson clover, alfalfa) and hairy vetch/wheat promoted the growth of larger, more metabolically active microbial populations, compared with the other legume systems and continuous corn.

Soil Pre-plant Nitrate Test and Pre-sidedressed Nitrate Test

While there was no effect of previous crops on soil PPNT at St-Mathieu-de-Beloeil (Table 4), the field at St-Lambert-de-Lauzon showed that except for the grain legumes and legumes intercropped with corn, all the previous legume crops increased the soil PPNT over the control with no legumes (Table 5). Compared with a control, increases in soil PPNT from alfalfa were more than 80%, more than 48% for hairy vetch/wheat, more than 42% for crimson clover and more than 40% for hairy vetch. As soil PPNT analysis measures soil nitrate concentration early in the growing season (Nyiraneza et al., 2010), it accounts for residual soil NO_3^-–N from the previous growing season. Increased soil nitrate concentrations were related to amounts of N returned to the soil (Table 3) and may indicate high mineralization rate of legumes incorporated in previous fall. Other researchers have noted a site-specific response of PPNT, as Sheaffer et al. (2001) observed significant increases in soil PPNT following incorporation of annual medic and berseem clover in previous fall at Becker, MN, and not at Rosemount, MN.

At both locations, previous legume crops significantly increased soil PSNT compared with the control with no legume (Tables 4 and 5). At St-Mathieu-de-Beloeil, incorporation of legumes (hairy vetch, alfalfa, and crimson clover) solely cropped or intercropped with wheat significantly increased soil PSNT while grain legumes (dry pea, dry bean, and soybean) had no significant effect on soil PSNT compared with the control with no legumes (Table 4). Compared with a control, the highest increase in soil PSNT was recorded for hairy vetch/wheat (+37%) followed by hairy vetch (+29%), alfalfa (+25%) and crimson clover, crimson clover/wheat (+20%) and pea (+19%). In contrast, soil PSNT levels declined following legumes [crimson clover (–13%) and alfalfa (–23%)] intercropped with corn, which also had the lowest N input in their residues (Tables 2 and 3), suggesting N immobilization due to corn residue decomposition. At St-Lambert-de-Lauzon, the greatest increases in soil PSNT were also observed for legumes in monoculture (alfalfa [+110%] followed by hairy vetch [+49%], hairy vetch/wheat and crimson clover [+25%]). The remaining previous legume crops showed similar soil PSNT as the control with no legumes (Table 5).

Table 5. Effects of preceding crops on pre-plant soil nitrate (PPNT), pre-sidedress nitrate (PSNT), alkaline phosphatase, and dehydrogenase at St-Lambert-de-Lauzon (Québec, Canada) during the 2012 cropping season.

Preceding crops	PPNT (0–30 cm)	PSNT (0–30 cm)	Alkaline phosphatase	Dehydrogenase
	— mg NO_3^-–N kg^{-1} —		mmol PNP† g^{-1} soil h^{-1}	mmol TPF g^{-1} soil h^{-1}
1. Corn (control)	6.16	10.15	152	60
2. Dry pea	7.44	10.65	158	73
3. Dry bean	6.83	11.90	168	65
4. Soybean	6.48	11.31	153	61
5. Alfalfa	11.09	21.30	163	69
6. Hairy vetch	8.64	15.10	159	57
7. Crimson clover	8.76	12.70	156	63
8. Crimson clover/wheat	6.64	11.04	154	59
9. Field pea/wheat	8.79	10.86	161	74
10. Hairy vetch/wheat	8.43	13.80	168	73
11. Crimson clover/corn	5.47	9.89	163	69
12. Alfalfa/corn	6.87	13.80	156	67
13. Hairy vetch/corn	6.32	9.57	171	58
	Analysis of variance (*P* value)			
Preceding crop effect	0.0475	0.0231	ns‡	ns
Contrasts				
1 vs. others	0.0389	0.0507	ns	ns
1 vs. 2, 3, and 4	ns	ns	ns	ns
1 vs. 5,6 and 7	0.0013	0.0030	ns	ns
1 vs. 8, 9 and10	0.0482	ns	ns	ns
1 vs. 11, 12, and 13	ns	ns	ns	ns
2, 3, and 4 vs. 5, 6, and 7	0.0010	0.0462	ns	ns
5, 6, and 7 vs. 8, 9, and 10	ns	0.0356	ns	ns
5, 6, and 7 vs. 11, 12, and 13	0.0028	0.0328	ns	ns
8, 9 and10 vs. 11, 12, and 13	0.0061	ns	ns	ns

† PNP, *p*-nitrophenol; TPF, triphenyltetrazolium formazan.

‡ ns, not significant.

Increases in soil nitrate in mid-growing season were often reported after plow-down of legumes such as alfalfa and hairy vetch (Griffin et al., 2000). Numerous researches support that PSNT test could be an indicator of N transfer from previous legume (Fox et al., 1989; Griffin et al., 2000; Nyiraneza et al., 2010). In the current study, soil PSNT levels were still far below the critical value (25 mg NO_3^-–N kg^{-1}) determined for corn in humid regions (Fox et al., 1989; Hesterman et al., 1992), indicating that sidedress N fertilizer application would be recommended, regardless of the fact that some previous legume crops may supply enough N to support crop growth of the subsequent grain crops. Still, Griffin et al. (2000) found that PSNT following incorporation of alfalfa and hairy vetch residues exceeded the critical value for corn cultivated in Maine, suggesting that both legume crops supplied all or nearly N required for subsequent corn production.

Soil Macroaggregates and Mean Weight Diameter of Aggregates

Soil macroaggregates (>0.25- mm) represented 79 to 97% of the soil aggregates at St-Mathieu-de Beloeil (Table 6) and 52 to 71% of soil aggregates at St-Lambert-de-Lauzon (data not shown). Even though aggregation was unexpectedly high at St-Mathieu-de Beloeil, the proportion of > 5-mm macroaggregates as well as mean weight diameter of aggregates (MWD) were further increased ($P < 0.05$) by previous legume crops compared with the control (Table 6). Compared with a control, the highest increases of the 5-mm aggregate proportion (+28% to +39%) and MWD (+9% to +13%) were recorded for monocropped legumes (alfalfa, hairy vetch, and crimson clover) and for hairy vetch/wheat. In contrast, grain legumes (pea, soybean, and dry bean) and legumes intercropped with corn (crimson clover/corn, alfalfa/corn, and hairy vetch/corn) that returned lowest biomass into the soil (Tables 2 and 3) did not significantly increase the proportion of >5-mm soil macroaggregates and the MWD of aggregates, compared to continuous corn as control.

Our data agree with previous studies that showed positive effect of legume-based rotations on soil aggregation (McVay et al., 1989; Haynes and Beare, 1997). McVay et al. (1989) also noted important improvement of soil aggregation stability in response to biomass incorporation from hairy vetch. Sandoval et al. (2007) found a positive response in aggregation and stability of soil aggregates when legumes (pink clover, white clover, and alfalfa) were incorporated into the soil in a crop rotation that included wheat, oat, and corn.

In the present study, the greatest proportion of soil macroaggregates >5 mm and MWD were obtained following alfalfa, hairy vetch, crimson clover, and hairy vetch/wheat that also induced the highest microbial activities (Table 4). These legume crops having lower C/N ratio (Table 2) are expected to have a larger proportion of labile fractions (cellulose, hemicellulose), which have promoted a rapid growth of soil

Table 6. Effects of preceding crops on soil macroaggregates and aggregate mean weight diameter (MWD) at St-Mathieu-de-Beloeil (Québec, Canada) during the 2012 cropping season.

Preceding crops	>5 mm	5–2 mm	2–1 mm	1–0.25 mm	MWD
	%				mm
1. Corn (control)	30.9	32.0	14.3	8.7	3.4
2. Dry pea	35.8	29.3	11.7	7.6	3.4
3. Dry bean	31.6	27.2	12.1	7.7	3.9
4. Soybean	32.9	33.3	17.5	9.9	3.3
5. Alfalfa	39.9	32.1	14.1	10.2	3.8
6. Hairy vetch	42.9	31.8	13.7	8.3	3.7
7. Crimson clover	39.5	29.5	12.7	8.8	3.7
8. Crimson clover/wheat	27.1	31.4	15.0	9.5	3.1
9. Field pea/wheat	34.7	30.3	12.9	7.6	3.6
10. Hairy vetch/wheat	39.6	35.2	15.1	6.8	3.9
11. Crimson clover/corn	34.9	28.1	14.6	6.9	3.7
12. Alfalfa/corn	32.8	30.0	14.2	8.8	3.4
13. Hairy vetch/corn	34.2	29.5	14.4	8.5	3.5
	Analysis of variance (*P* value)				
Preceding crop effect	0.0437	ns†	ns	ns	0.0293
Contrasts					
1 vs. others	0.0236	ns	ns	ns	0.0359
1 vs. 2, 3, and 4	ns	ns	ns	ns	ns
1 vs. 5,6 and 7	0.0218	ns	ns	ns	0.0178
1 vs. 8, 9 and10	ns	ns	ns	ns	ns
1 vs. 11, 12, and 13	ns	ns	ns	ns	ns
2, 3, and 4 vs. 5, 6, and 7	0.0164	ns	ns	ns	0.0213
5, 6, and 7 vs. 8, 9, and 10	0.0232	ns	ns	ns	0.0461
5, 6, and 7 vs. 11, 12, and 13	0.0325	ns	ns	ns	0.0188
8, 9 and10 vs. 11, 12, and 13	ns	ns	ns	ns	ns

† ns, not significant.

microorganisms and induced soil aggregation as also found by Bipfubusa et al. (2008) in a study with paper mill sludges.

In the current research, incorporation of legume residues did not however significantly improve the soil structure or microbial activities at St-Lambert-de-Lauzon. The warmer climate at St-Mathieu-de-Beloeil location probably stimulated the turnover rate of incorporated legume residues and thereby, enhanced production of microbial-derived organic binding agents such as polysaccharides, mainly bacterial mucilages and fungal hyphae. This argumentation is strengthened by increases in soil microbial activities as measured by dehydrogenase and alkaline phosphatase activities (Table 4).

Effects of Previous Legume Crops on Corn and Wheat Yield, Nitrogen Uptake and Efficiency, and Nitrogen Response

Corn and Wheat Yield, Nitrogen Uptake, and Agronomic Nitrogen Efficiency

Averaged across all N fertilizer rates, corn grain yields varied from 9558 to 12,153 kg ha^{-1} at St-Mathieu-de-Beloeil and from 6380 to 7443 kg ha^{-1} at St-Lambert-de-Lauzon (Tables 7 and 8). Average wheat yields ranged from 3315 to 4081 kg ha^{-1} at St-Mathieu-de-Beloeil and from 2279 to 3189 kg ha^{-1} at St-Lambert-de-Lauzon. Grain yields were similar to regional averages for these areas published by Institut de la Statistique du Québec in 2012: 9210 kg corn grain ha^{-1} and 3950 kg wheat grain ha^{-1} in southern region of Montérégie, the region where St-Mathieu-de-Beloeil is located, and 6730 kg corn grain ha^{-1} and 2880 kg wheat grain ha^{-1} in the northern region of Chaudières-Appalaches,where we find St-Lambert-de-Lauzon. (http://www.stat.gouv.qc.ca/statistiques/agriculture/grandes-cultures/index.html). Our data showed that corn and wheat yield averages obtained at St-Mathieu-de-Beloeil were greater by 2377 to 5556 kg ha^{-1} and by 669 to 1294 kg ha^{-1}, respectively, than those obtained at St-Lambert-de-Lauzon. In a study conducted on 62 fields from different regions of Québec, Nyiraneza et al. (2010) also found that corn grain yields achieved in Montérégie were higher by at least 5 t ha^{-1} than those obtained in cooler regions of Québec. Corn N uptake varied between 125 and 167 kg N ha^{-1} at St-Mathieu-de-Beloeil and 99 to 121 kg N ha^{-1} at St-Lambert-de-Lauzon while wheat N uptake ranged from 60 to 92 kg N ha^{-1} at St-Mathieu-de-Beloeil, and 56 to 80 kg N ha^{-1} at St-Lambert (Tables 7 and 8).

At St-Mathieu-de-Beloeil, corn and wheat grain yield and N uptake were significantly affected by the preceding crops and N fertilizer rates (Table 7). Interactions between these effects on grain yield and N uptake were significant ($P < 0.01$) for corn but not for wheat. Orthogonal polynomial contrasts showed that N fertilizer rate had significant quadratic effects ($P < 0.001$) on corn and wheat yield (Table 7). Contrast analysis showed that higher corn yield and N uptake were obtained following monocropped legumes (5, 6, and 7) compared with other legume systems and continuous corn (2, 3, and 4; 8, 9, and 10; 11, 12, and 13).

The greatest increase of corn and wheat grain yields and N uptake occurred in fields where the previous crop was

Table 7. Effects of preceding crops and nitrogen fertilization on corn and wheat grain yield, N uptake and agronomic nitrogen efficiency (ANE) at St-Mathieu-de-Beloeil (Québec, Canada) during 2012 cropping season†.

	Corn grain			Wheat grain		
Preceding crops	Grain yield	N	ANE	Grain	N	ANE
	kg ha^{-1}		kg grain kg N^{-1}	kg ha^{-1}		kg grain kg N^{-1}
1. Corn (control)	10,265	141.54	91	3437	62.15	78
2. Dry pea	10,380	151.27	96	3655	69.30	82
3. Dry bean	10,243	135.88	91	3400	59.77	77
4. Soybean	10,056	142.97	98	3753	74.04	80
5. Hairy vetch	11,765	162.76	97	3841	86.09	87
6. Crimson clover	11,960	167.22	108	4040	87.13	92
7. Alfalfa	10,925	149.10	96	3296	67.49	75
8. Crimson clover/wheat	10,003	132.62	98	3488	64.89	80
9. Field pea/wheat	10,216	137.35	91	3570	65.77	69
10. Hairy vetch/wheat	12,153	160.42	114	4081	92.12	94
11. Crimson clover/corn	9,558	126.62	83	3351	68.01	77
12. Alfalfa/corn	9,599	124.78	84	3315	63.70	74
13. Hairy vetch/corn	10,408	143.05	101	3751	71.44	87
		Analysis of variance (*P* value)				
Preceding crops	0.0019	0.0051	ns‡	0.0055	<0.0001	ns
N fertilizer rate	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Preceding crops × N fertilizer rate	0.0046	0.0059	0.0001	ns	ns	0.0031
Linear effect of N fertilizer rate	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Quadratic effect of N rate	<0.0001	0.0042	0.0008	0.0001	ns	0.0052
Contrasts						
1 vs. others	ns	ns	ns	0.0461	0.0025	ns
1 vs. 2, 3, and 4	ns	ns	ns	ns	ns	ns
1 vs. 5,6 and 7	0.0019	0.0308	ns	0.0274	<0.0001	ns
1 vs. 8, 9 and10	ns	ns	ns	0.0437	<0.0001	ns
1 vs. 11, 12, and 13	ns	ns	ns	ns	ns	ns
2, 3, and 4 vs. 5, 6, and 7	0.0318	0.0282	ns	ns	0.0001	ns
5, 6, and 7 vs. 8, 9, and 10	0.0453	0.0354	ns	ns	ns	ns
5, 6, and 7 vs. 11, 12, and 13	0.0236	0.0431	ns	0.0423	0.0001	ns
8, 9 and10 vs. 11, 12, and 13	0.0452	0.0253	ns	0.0041	0.0055	ns

† Data of grain yield, N uptake and N fertilizer efficiency are the average of different N rates.

‡ ns, not significant.

hairy vetch, hairy vetch/wheat, crimson clover and alfalfa at St-Mathieu-de- Beloeil. Other studies also reported corn yield improvements due to N contribution from alfalfa and crimson clover at a variety of sites and environmental conditions (Bruulsema and Christie, 1987; Zhang and Blevins, 1996; Varvel and Wilhelm, 2003; Ballesta and Lloveras, 2010). Benefits of hairy vetch were observed for the subsequent corn crop (Ebelhar et al., 1984; Hoyt, 1987; Zhang and Blevins, 1996). Similarly to previous studies, our data suggest that benefits of those legumes systems are related to their high N supplying capacity (Tables 2 and 3). However, their contribution to succeeding cereal grain yields might also be related to the non N-effects, as suggested by improvement of soil structure and microbial activities at St-Mathieu-de-Beloeil (Tables 4 and 6).

At St-Lambert-de-Lauzon, average corn grain yield and N uptake did not significantly differ due to the previous crops but showed a significant linear effect of N fertilizer rates (Table 8). Average wheat grain yield and N uptake were significantly affected by previous crops, N fertilizer rate and interactions between the two main effects. Orthogonal contrasts showed that N fertilizer rate had a significant linear effect ($P < 0.001$) on corn and wheat yield and N uptake, regardless of the previous crop (Table 8). Even if the amounts of aboveground biomass and N returned to the soil were similar between the two locations (Tables 2 and 3), this low contribution of legumes to N nutrition of the following grain crop at St-Lambert-de-Lauzon was probably due to cool climate conditions in 2012 (Table 1) that resulted in low N mineralization from crop residues.

Agronomic nitrogen efficiency indicates the ability of plants to use N fertilizer to produce grain yield. Averaged over all N fertilizer rates, corn ANE varied between 83 and 114 kg grain kg^{-1} N at St-Mathieu-de-Beloeil (Table 7), and from 22 to 37 kg grain kg^{-1} N at St-Lambert-de-Lauzon (Table 8). Wheat ANE ranged from 69 to 94 kg grain kg^{-1} N at St-Mathieu-de-Beloeil, and from 51 to 73 kg grain kg^{-1} N at St-Lambert-de-Lauzon. At St-Mathieu-de-Beloeil, the effect of the previous legume systems on corn and wheat ANE was not significant at $P < 0.05$ (Table 7). Both corn and wheat ANE were significantly influenced by N fertilizer application and by the previous crops × N fertilizer rate interactions ($P < 0.001$) (Table 7). The occurrence of significant interactions between previous crops and N fertilizer rates might reflect differences in the amount and time that N is released from previous crop residues through mineralization. Orthogonal contrasts show that

Table 8. Effects of preceding crops and nitrogen fertilization on corn and wheat grain yield, N uptake, and agronomic nitrogen efficiency (ANE) at St-Lambert-de-Lauzon (Québec, Canada) during 2012 cropping season†.

	Corn grain			Wheat grain		
Preceding crops	Grain yield	N	ANE, kg kg^{-1}	Grain yield	N	ANE, kg kg^{-1}
	kg ha^{-1}		kg grain kg N^{-1}	kg ha^{-1}		kg grain kg N^{-1}
1. Corn (control)	6424	104.90	29	2374	60.20	55
2. Dry pea	6409	103.81	29	2780	68.10	65
3. Dry bean	6572	106.88	31	2611	65.43	58
4. Soybean	6287	98.84	22	2756	71.65	60
5. Hairy vetch	6973	115.37	35	2918	75.86	65
6. Crimson clover	6404	104.39	37	2995	75.98	66
7. Alfalfa	7267	115.20	29	3189	80.32	73
8. Crimson clover/wheat	7626	121.10	30	2504	63.14	57
9. Field pea/wheat	6940	111.87	30	2396	62.22	55
10. Hairy vetch/wheat	7443	121.24	27	2822	73.26	67
11. Crimson clover/corn	6380	99.83	25	2279	56.19	51
12. Alfalfa/corn	6718	106.73	24	2646	67.68	63
13. Hairy vetch/corn	7252	116.88	31	2457	62.15	54
			Analysis of variance (*P* value)			
Preceding crops	ns‡	ns	ns	0.0451	0.0345	ns
N fertilizer rate	0.0027	0.0012	0.0036	0.0062	0.0010	0.0001
Preceding crops × N fertilizer rate	ns	ns	ns	0.0451	0.4978	ns
Linear effect of N fertilizer rate	<0.0001	0.0013	<0.0001	0.0001	0.0001	<0.0001
Quadratic effect of N rate	ns	ns	ns	ns	ns	0.0532
Contrasts						
1 vs. others	ns	ns	ns	ns	ns	ns
1 vs. 2, 3, and 4	ns	ns	ns	ns	ns	ns
1 vs. 5,6 and 7	ns	ns	ns	0.0436	0.0393	ns
1 vs. 8, 9 and10	ns	ns	ns	ns	ns	ns
1 vs. 11, 12, and 13	ns	ns	ns	ns	ns	ns
2, 3, and 4 vs. 5, 6, and 7	ns	ns	ns	ns	ns	ns
5, 6, and 7 vs. 8, 9, and 10	ns	ns	ns	ns	ns	ns
5, 6, and 7 vs. 11, 12, and 13	ns	ns	ns	0.0423	0.0384	ns
8, 9 and10 vs. 11, 12, and 13	ns	ns	ns	ns	ns	ns

† Data of grain yield, N uptake and N fertilizer efficiency are the average of different N rates.

‡ ns, not significant.

Table 9. Regression analysis of corn grain yield response to N fertilizer rate at St-Mathieu-de Beloeil (Québec, Canada) during the 2012 cropping Season.

	P value			Regression parameters†					
Preceding crops	N effect	Linear effect	Quadratic effect	*a*	*b*	*c*	r^2	Maximum yield	Optimal N rate
								kg ha^{-1}	
1. Corn (control)	0.0001	<0.0001	0.0023	5380.00	40.04		0.88	12,290	
2. Dry pea	0.0523	0.0469	ns‡	9946.84	20.42		0.33	13,168	
3. Dry bean	0.0001	<0.0001	0.0008	6657.33	35.85		0.82	12,963	
4. Soybean	0.0001	<0.0001	ns	7931.47	25.24		0.89	12,979	
5. Hairy vetch	0.0019	0.0001	0.0175	7982.87	54.56	0.12	0.74	13,169	141
6. Crimson clover	0.0423	0.0039	0.0031	9945.67	49.54	0.16	0.59	13,650	135
7. Alfalfa	0.0009	0.0001	0.0005	6947.87	95.85	–0.39	0.81	12,838	123
8. Crimson clover/wheat	0.0001	<0.0001	0.0023	6280.67	37.23		0..92	13,023	
9. Field pea/wheat	0.0001	<0.0001	0.0016	6455.67	37.60		0.92	13,303	
10. Hairy vetch/wheat	0.0007	0.0001	0.0010	6170.03	82.18	–0.28	0.90	12,285	149
11. Crimson clover/corn	0.0005	<0.0001	0.0326	5494.8	40.64		0.91	12,828	
12. Alfalfa/corn	0.0017	0.0001	ns	6313.6	32.85		0.80	12,198	
13. Hairy vetch/corn	0.0009	<0.0001	0.0422	7647.37	37.50		0.91	14,172	

† *a*, *b*, and *c* represent the intercept (check yield), linear term, and quadratic term, respectively.

‡ ns, not significant.

N fertilizer application had significant quadratic effects on both cereals ANE. According to Bundy (2006) and Rahimizadeh et al. (2010), this means that the first increments of added N fertilizer were the most efficient at increasing yield while the efficiency of N applied declined as yields approach the maximum yield.

Data obtained at St-Lambert-de-Lauzon have shown that previous legume crops had little effect on corn and wheat ANE (Table 8). Corn and wheat ANE was significantly influenced by N fertilizer application and the interaction of previous legumes and N fertilizer rates was not significant (Table 8). Orthogonal contrast analysis showed that N fertilizer application had a significant linear effect on corn and wheat ANE. This shows that crops mostly used readily available N from fertilizer rather than from legumes residues, probably due to slow N mineralization at this location.

Our results show that 4 out of 12 legume crop systems significantly affected the subsequent cereal crop yield and N nutrition. Forage legumes grown under monoculture (crimson clover, alfalfa, and hairy vetch) and hairy vetch/wheat produced higher N input (50–134 kg N ha^{-1}) and higher corn and wheat yields than grain legumes and legumes intercropped with wheat or corn.

Grain legumes produced less organic residues and less N input and did not impact the subsequent corn and wheat yields and N nutrition, probably because the N-rich grain is harvested and the remaining residues contribute little to net N addition to the soil (Beck et al., 1991). Except for hairy vetch/wheat, all legumes intercropped with wheat or corn did not impact crop yields and N nutrition. A cereal intercropped with a legume has a faster growth rate and more extensive root system, particularly a larger mass of fine roots (Lehmann et al., 1998) and therefore creates competition with associated legume for soil inorganic N (Carr et al., 2004). In both studied locations, legumes intercropped with corn produced lower amounts of dry matter and lower N accumulation (Tables 2 and 3), and immobilization may also have occurred during corn stalk decomposition. Another reason that intercropping legumes with cereals may slow N mineralization and availability is because of higher C/N ratio of their residues as shown in Tables 2 and 3 (Hauggaard-Nielsen et al., 2003).

Nitrogen credit for the above-cited legume crops was calculated based on corn and wheat N uptake (N uptake legume treatment-N uptake control (Tables 7 and 8), and varied from 8 to 26 kg N for corn and from 5 to 30 kg N ha^{-1} for wheat at St-Mathieu-de-Beloeil. Nitrogen credit varied from 10 to 16 kg N ha^{-1} for corn and from 13 to 20 kg N ha^{-1} for wheat at St-Lambert-de-Lauzon location. Results showed that N derived from legume crops was low and alone could not justify increased yields, which indicates that the “rotation effect” also called “non-N related effects” was important. The rotation effect is attributed to improved soil conditions that have favored corn and wheat growth and N nutrition, enhanced N fertilizer use efficiency and increased N fertilizer replacement value of legumes.

It was unexpected to find a beneficial rotation effect from forage legumes (alfalfa, crimson clover, hairy vetch, hairy vetch/wheat) on corn and wheat yield and N nutrition, and on soil properties within 1 yr at the St-Mathieu-de-Beloeil site. This was attributed to the higher dry matter and N input from forage legumes compared with other legume systems (Tables 2 and 3). The warmer climatic conditions at St-Mathieu-de-Beloeil than at St-Lambert-de-Lévis (Table 1) probably caused faster mineralization of legume residues and contributed to the higher corn and wheat yields, higher N availability, and rapid improvement of soil properties.

Corn and Wheat Nitrogen Response

In some studies, incorporation of legume residues in a temperate environment fully satisfied N requirements of the subsequent corn (Griffin et al., 2000). In the present study, addition of N fertilizer significantly increased wheat and corn yield at both locations, regardless the preceding crop. This means that N contribution from the previous crop was not sufficient to achieve the grain crop N requirements and that supplemental N fertilizer was required to achieve maximum crop productivity.

At St-Lambert-de-Lauzon, orthogonal contrasts showed that N fertilizer rate had a significant linear effect ($P < 0.001$) but had no significant quadratic effect on corn yield regardless the previous crop (Table 8). Therefore, it was not possible to

Table 10. Regression analysis of wheat grain yield response to N fertilizer rate at St-Mathieu-de Beloeil (Québec, Canada) during the 2012 cropping season.

Preceding crops	*P* value			Regression parameters†			r^2	Maximum yield	Optimal N rate
	N effect	Linear effect	Quadratic effect	*a*	*b*	*c*		kg ha^{-1}	
Corn (control)	0.0001	<0.0001	ns‡	2406.87	19.88		0.84	3817	
Dry pea	0.0016	0.0001	ns	3021.93	15.82		0.70	4322	
Dry bean	0.0001	<0.0001	ns	2640.20	19.01		0.83	4083	
Soybean	0.0009	0.0001	ns	3165.53	17.18		0.76	4475	
Hairy vetch	0.0314	0.0019	0.0217	3156.12	29.48	–0.21	0.68	4432	51
Crimson clover	0.0206	0.0067	ns	3576.93	11.57		0.60	4445	
Alfalfa	0.0007	<0.0001	0.0205	2194.75	44.14	–0.28	0.89	3954	76
Crimson clover/wheat	<0.0001	<0.0001	<0.0001	2498.17	43.88	–0.32	0.92	3984	68
Field pea/wheat	0.0043	<0.0001	ns	2819.80	18.67		0.75	4260	
Hairy vetch/wheat	0.0062	0.0001	0.0037	3336.32	47.11	–0.55	0.80	4338	43
Crimson clover/corn	<0.0001	<0.0001	0.0041	2400.02	38.21	–0.24	0.56	3917	79
Alfalfa/corn	0.0009	<0.0001	ns	2522.33	19.81		0.86	4012	
Hairy vetch/corn	0.0026	0.0001	0.0425	3015.85	30.75	–0.21	0.61	4163	75

† *a*, *b*, and *c* represent the intercept (check yield), linear term, and quadratic term, respectively.

‡ ns, not significant.

calculate the optimum N fertilizer rates for any previous crops for this location since both wheat and corn yields increased with N fertilizer rate up the highest rate tested (80 kg N ha^{-1}) for wheat and 200 kg N ha^{-1} for corn.

At St-Mathieu-de- Beloeil site, the amount of N fertilizer required for reaching maximum corn grain yield, referred to optimal N fertilizer rate, was 123 kg N ha^{-1} following crimson clover, 135 kg N ha^{-1} following hairy vetch, 141 kg N ha^{-1} following alfalfa, and 149 kg N ha^{-1} following hairy vetch/wheat intercrop, compared with 200 kg ha^{-1} or more for the other legume systems and the control (Table 9).

For wheat, the optimum N fertilizer rate was 43 kg N ha^{-1} following hairy vetch/wheat intercrop, 51 kg N ha^{-1} following alfalfa, 68 kg N ha^{-1} following crimson clover/wheat intercrop, 75 to 79 kg N ha^{-1} following crimson clover, hairy vetch/corn, and crimson clover/corn intercrops compared with 80 kg N ha^{-1} or more for the other legume systems and the control (Table 10). Incorporation of these legumes could have allowed potential N fertilizer savings of 51 to 77 kg N ha^{-1} for corn and of 5 to 37 kg N ha^{-1} for wheat, in comparison with 175 N ha^{-1} and 90 N ha^{-1} which are generally recommended for corn and wheat, respectively. The most interesting preceding crops were hairy vetch, hairy vetch/wheat, alfalfa, and crimson clover since they reduced N fertilizer requirements to the greatest extent, while producing maximum corn and wheat grain yields.

Results of this study show that in growing conditions similar to those encountered at St-Mathieu-de-Beloeil, forage legumes need to be grown in monoculture than intercropped to produce high aboveground biomass and N returns, to increase subsequent crop yields and N nutrition, and to improve soil physical and biological soil properties.

CONCLUSIONS

The current study demonstrated that four legume systems (hairy vetch, crimson clover, alfalfa, and hairy vetch/wheat) increased yields and N nutrition of corn and wheat at St-Mathieu-de-Beloeil site and of wheat only at St-Lambert-de-Lauzon. Also, soil macroaggregates, aggregate MWD, phosphatase alkaline, and dehydrogenase activity were increased following the above-cited legumes at St-Mathieu-de Beloeil site only. Benefits of preceding legume crops on soil properties and on crop yields, N nutrition and N use efficiency were more noticeable at warmer site than at cooler location, probably due to better conditions for crop growth and residue mineralization. Legume grown under monoculture (hairy vetch, crimson clover, alfalfa) and hairy vetch/wheat also produced the greatest N fertilizer replacement value for subsequent corn (37–77 kg N ha^{-1}) and wheat (5–37 kg N ha^{-1}), although N credit for those legumes was <30 kg N ha^{-1}. This implies that the non-N effects of these legume crops such as stimulation of enzyme activity and soil aggregation exerted an important positive effect on grain crop yield and N nutrition. Our results show that under warm climatic conditions, including forage legume crops in the rotation can provide a direct N contribution and indirect benefits to crops by improving soil fertility. Therefore grain crop yield and N nutrition are expected to improve in the years following forage legume crops, which should encourage agricultural producers to include legumes in their crop rotations.

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