REDUCED TILLAGE IN ORGANIC CROPPING SYSTEMS ON THE CANADIAN PRAIRIES

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ABSTRACT

Organic producers on the Canadian prairies rely heavily on tillage for weed control and soil nutrient management. Intensive tillage degrades soil quality, and therefore efforts to reduce tillage in organic agriculture are increasing. Research has focused on replacing tillage for green manure termination with alternative low-disturbance methods. The roller-crimper terminates green manures by rolling over the crop and creating a mulch that is anchored to the ground. Rolled mulches can suppress weeds and conserve soil moisture, but surface-placed residues can delay N mineralization and result in subsequent yield loss.

Three field studies were conducted in Saskatchewan, Alberta and Manitoba using the roller-crimper to determine the extent to which tillage can be reduced in organic systems without negatively impacting nutrient availability and yield. At two sites in Saskatchewan, the effects of termination timing (early flower, late flower, early pod) and termination method (rolling, mowing, tillage) of field pea (*Pisum sativum*) and faba bean (*Vicia faba*) green manures on soil properties and spring wheat (*Triticum aestivum*) performance were measured in 2009 and 2010. Faba bean did not establish well and failed as a green manure crop. Termination timing and method affected soil properties in the first year, but did not affect wheat yield significantly. Wheat yield was equivalent in the rolled and mowed treatments to the tilled treatment, indicating field pea termination without incorporation does not inhibit wheat yield under moist conditions.

Soil inorganic N was measured in the spring of 2011 following green manure (field pea/barley [*Hordeum vulgare*]) termination in 2010 by tillage, rolling, rolling + fall tillage, and mowing at two locations. Inorganic N was highest in the tilled plots at both sites, but effects on 4 wk mineralized N (N_{min}) differed between sites. When the green manure C:N was narrow (14:1), tillage resulted in lower N_{min} than the other treatments; when the C:N was wider (20:1), tillage resulted in the highest N_{min}. These results confirm mineralization rates vary with residue placement and N content.

Lastly, the effect of 2 yr of continuous no-tillage (NT) or conventional tillage on available N and P, soil microbial biomass (SMB), and oat (*Avena sativa*) N and P uptake was measured at one site in 2010. Overall, tillage regime did not affect N and P availability, SMB, or oat nutrient uptake. Microbial biomass C and inorganic N tended to be higher in the NT treatment at 0 to 5 cm, suggesting differences may become apparent in the long term.

This research confirms that a reduction in tillage is possible in organic systems on the Canadian prairies. The degree of reduction is dependent on the green manure used, soil and climatic factors, and the goals of the producer.

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DEDICATION

To my mom. Strong and beautiful, she is so lovely.

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LIST OF ABBREVIATIONS

AAFC	Agriculture and Agri-Food Canada
BNF	Biological nitrogen fixation
$CHCl_3$	Chloroform
C:N	Carbon to nitrogen ratio
CO_2	Carbon dioxide
C:P	Carbon to phosphorus ratio
CT	Conventional tillage
FC	Field capacity
KCl	Potassium chloride
K_2SO_4	Potassium sulfate
LTA	Long-term average
n	Number of observations
N_2	Di-nitrogen
NA	Natural abundance
%Ndfa	Percent nitrogen derived from the atmosphere
NH_4/NH_4^+	Ammonium
N_{min}	mineralizable N
NO_3/NO_3^-	Nitrate
NT	No-tillage
OACC	Organic Agriculture Centre of Canada
OSC	Organic Science Cluster
P	Probability
PO_4	Phosphate
r	Pearson correlation coefficient
RCBD	Randomized complete block design
SMA-ADF	Saskatchewan Ministry of Agriculture-Agriculture Development Fund
SMB	Soil microbial biomass
SMB-C	Soil microbial biomass carbon
SMB-N	Soil microbial biomass nitrogen
SOC	Soil organic carbon
SOM	Soil organic matter
TOC	Total organic carbon
TN	Total nitrogen

1. INTRODUCTION

Organic management and conservation tillage are increasingly common agricultural practices across the Canadian prairies, and both have emerged as farming systems that enhance sustainability and soil quality (Mader et al., 2002; Miller et al., 2008). The adoption of conservation tillage in conventional agriculture has enhanced soil organic matter (SOM), reduced soil erosion, and conserved soil moisture (Lafond et al., 1992; Malhi et al., 2008); however, the management system is heavily reliant on herbicides for weed control. In contrast, agrochemicals are prohibited in organic agriculture and tillage is one of the only management tools available to producers. Tillage is relied upon for weed control, seedbed preparation, and also nutrient management through the incorporation of crop residues and stimulation of N mineralization (Watson et al., 2002). The frequent use of tillage is a key challenge facing the long-term sustainability of organic agriculture, as tillage is known to accelerate SOM decomposition and can decrease soil quality (Franzluebbers et al., 1999).

Interest in reducing tillage in organic agriculture is increasing, but producers and researchers are uncertain whether soil fertility, weed suppression, and profitable yields can be maintained under reduced tillage practices (Blackshaw et al., 2010). Eliminating tillage from organic rotations reduced crop yields as a result of heavy weed pressure and delayed N mineralization (Drinkwater et al., 2000; Peigné et al., 2007; Vaisman et al., 2011). However, reducing the number of tillage passes (Vaisman et al., 2011) or the tillage depth (Teasdale et al., 2007; Berner et al., 2008; Krauss et al., 2010) in organic systems can positively impact soil N status, indices of soil quality (microbial biomass and SOM), and crop yield.

A promising research area is the reduction of tillage during the green manure or cover crop phase of a rotation. Due to the large size of prairie farms, soil amendments and animal manure are not practical fertility sources, and instead producers rely on crop rotation, summerfallow, and green manures for nutrient management (Knight et al., 2010a). Green manures increase soil organic matter as compared to summerfallow (SOM) (Biederbeck et al., 1998), stimulate biological activity (Biederbeck et al., 2005), improve soil structure (Wallace, 2001), and increase potentially mineralizable N (Pikul et al., 1997). Use of green manures can also deplete soil moisture reserves to the detriment of the subsequent crop (Pikul et al., 1997;

Zentner et al., 2004), and increase organic farmers' dependence on tillage (Drinkwater et al., 2000). Studies in the United States and Canada demonstrated that green manure/cover crop termination by tillage can be replaced with alternative implements, such as the roller-crimper and flail mower, that leave residues on the soil surface. The roller-crimper rolls over a crop and crimps the stems, killing the plant but leaving the stem tissue intact and anchored to the soil. The rolled mulch can suppress weed growth and facilitate direct seeding, and studies in the southern United States have shown that crops can be successfully seeded into rolled mulches (Mirsky et al., 2009; Mischler et al., 2010; Smith et al., 2011). Success of the roller has been greatest with high biomass cover crops that slowly decompose on the soil surface. Limited research has been conducted on green manure termination by the roller in Canada, where the climate and cropping systems present different challenges then the southern United States.

The following research examines the management of annual legume green manures across the Prairie Provinces in an effort to reduce tillage in organic production. The studies vary in the green manure crops used, the degree of tillage, and the year of study. Common to all studies is the comparison between termination by tillage or rolling and the use of a 'test' crop in the following year(s) to assess the effects of green manure termination.

The greater question driving this research was "to what extent can tillage be reduced in organic production systems without a negative effect on crop yields?" The specific research questions were: 1) as tillage is reduced in an organic cropping system, what is the effect on soil moisture? 2) Does lack of incorporation of green manure residues reduce the level of soil available N and P and cereal yield in the year(s) following termination? 3) What is the short-term effect of rolling *vs* tillage on soil microbial biomass (SMB), and what implications might this have for the long term? The objectives of the study were to: i) compare N_2 fixation and crop residue quality of field pea (*Pisum sativum*) and faba bean (*Vicia faba*) green manures at different termination dates (Chapter 3); ii) quantify the short-term effects of termination timing and termination method of field pea on soil inorganic N and P, moisture, SMB, and crop nutrient uptake in a green manure-wheat (*Triticum aestivum*) system (Chapter 3); iii) compare termination methods of a field pea/barley (*Hordeum vulgare*) green manure on 4 wk mineralized N (Chapter 4); and iv) measure the effect of two years of NT organic management on N and P availability and SMB in a green manure-flax (*Linum usitatissimum*)-oat (*Avena sativa*) system (Chapter 5).

2. LITERATURE REVIEW

"We know that nature's stores, rich as they once were on the Great Plains, will not always sustain us without our own re-investments. The nutrient reserves will not persist without us returning what we extract; the diversity of biota in and on the soil will not flourish without our conscious effort to uphold it; the life-giving humus will not re-build without us restoring what is decayed or eroded away; the land's quiet services of filtering water and air will not continue without us paying heed to them."
(H.H. Janzen, 2010)

2.1 Organic Agriculture on the Prairies

Organic agriculture: "a cultivation system that attempts to produce crops of maximal nutritional quality while respecting the environment and conserving soil fertility" (Garcia-Ruiz et al., 2008)

Awareness of the detrimental impacts of conventional agriculture on the environment, and the associated health risks, is becoming more widespread in Canadian society. The word 'sustainability' has entered all types of discourse from social to environmental issues – including conversations around food production and supply. Organic agriculture is recognized as a farming system that increases sustainability (Miller et al., 2008) through self-reliance and maintenance of soil fertility (Mader et al., 2002). The Canadian General Standards Board developed "Organic Production Systems General Principles and Management Standards" in 2006, and the standards became mandatory in 2009 (Government of Canada, 2006). The standards describe organic production as "… a holistic system designed to optimize the productivity and fitness of diverse communities within the agro-ecosystem, including soils organisms, plants, livestock and people" (Government of Canada, 2006). While the main goal of organic production is the development of sustainable enterprises that do not harm the environment (Government of Canada, 2006), it is also an important economic sector in Canada.

Analysis based on the 2008 sales of organic food concluded the organic sector in Canada is estimated to be worth 2 billion dollars annually, and this value is growing (Willer and Kilcher, 2011). In 2009, the Prairie Provinces – Alberta, Sakatchewan and Manitoba – accounted for approximately 83% of the nearly 700,000 ha of organically-farmed land in Canada (Macey, 2010). As of 2009 Saskatchewan alone had almost 400,000 ha in organic production and boasts the largest number of organic farms in the country (1123 out of 3914 total in Canada) (Macey, 2010). Field crops produced in the prairies occupy the most organic acreage in Canada. At an estimated 102,434 ha wheat/durum (*Triticum aestivum/durum*) was the front-runner in 2009, followed by oats (*Avena sativa*) at 44,539 ha (Macey, 2010).

Until recently, the rapid expansion in the organic sector was not matched by research efforts, particularly not in Saskatchewan (Knight and Shirtliffe, 2005). Because prairie farms occupy such a large percentage of the organic acreage in Canada, management of these large-scale grain farms has a potentially large environmental impact. Research leading to improved organic management strategies in the prairies is a worthy investment. With improved support from the Saskatchewan Ministry of Agriculture-Agriculture Development Fund (SMA-ADF) and Agriculture and Agri-Food Canada (AAFC), and the creation of the Organic Science Cluster (OSC) in 2009, organic research has expanded in the prairies. The OSC is a collaborative research effort between the Organic Agriculture Centre of Canada (OACC), the Organic Federation of Canada, AAFC, and industry partners to facilitate a nation-wide approach to organic science (OACC, 2010). Current OSC projects in the prairies include characterizing P availability and uptake, weed control in long-term organic rotations, organic cereal crop breeding, and reducing tillage in organic systems (OACC, 2010).

Producers themselves are continuously experimenting with new implements and management techniques to improve organic farming in their locale, and the frequency of controlled and province-wide experiments should increase with support from public and private sector. Crop rotations, soil fertility, soil quality/health, and weed management were the highest ranked research interests of organic producers surveyed in the Prairie Provinces in 2008 (Frick et al., 2008). Rotations for soil fertility (including green manures) and soil biology management ranked highest as specific soil concerns in Saskatchewan. Producers were also interested in the use of reduced tillage in organics to conserve soil moisture and maintain soil residue and aggregate size (Frick et al., 2008).

Reduced tillage increases soil organic matter (SOM) directly by slowing decomposition, primarily by lowering the amount of oxygen in the soil (Wolf and Snyder, 2003). Low-input farming systems such as organic agriculture rely on the cycling of nutrients from SOM to maintain soil fertility (Watson et al., 2002), and therefore practices that enhance SOM are beneficial. According to the Canadian Organic Standards soil fertility must be managed and enhanced by stimulating soil biological activity, balancing soil nutrient supply, and employing soil conservation practices such as minimum tillage (Government of Canada, 2006). Including legume green manures in crop rotations effectively increases soil biological activity and diversity, and returns organic matter to the soil (Lupwayi et al., 2004b; Biederbeck et al., 2005). No longer can we rely on the nutrient reserves of the rich Chernozemic soils on which we stand; focus must be drawn to replenishing and building the SOM reserves and not mining them (Janzen, 2010).

2.2 Tillage

Tillage is an ancient practice that was traditionally used to prepare seedbeds and eradicate weeds (Lal, 2007). Before the introduction of agrochemicals, tillage was a reliable form of weed control and a stimulus for nutrient cycling. Tillage stimulates mineralization from incorporated residues and also SOM as aggregates are broken up and exposed (Peigné et al., 2007). Residue and SOM mineralization is especially important in soils receiving little or no inputs to maintain crop yields. Tillage is still used in modern agriculture to control pests, diseases and weeds; loosen compacted soil; stimulate soil warming in the spring; incorporate chemical inputs and organic residues; and prepare beds for planting (Franzluebbers, 2004). However, the necessity of intensive tillage came under question as water and wind erosion became global issues and soil quality declined with decreased SOM (Lal, 2007). Mineralization is accelerated under conventional tillage because the residue-to-soil contact and soil aeration are increased, which stimulates microbial activity and decomposition (Lupwayi and Burr, 2010). Nutrients are made available for crop uptake, but the soil is left exposed and susceptible to evaporation and erosion. Soil organic matter is lost physically through erosion, and also with increased mineralization rates as microorganisms transform organic C into CO_2 (Wolf and Snyder, 2003). As SOM is lost, soil fertility and structure decline in an agricultural system, increasing the dependence on cultivation to stimulate mineralization and aeration (Gliessman, 2007). Therefore, low-input cropping systems can become dependent on cultivation.

2.2.1 Reduced tillage and no-tillage

Considering these detrimental effects of tillage, there has been a strong movement towards reducing tillage in conventional cropping systems. Conservation tillage has emerged over the last 40 yr and encompasses several different forms of less-intensive tillage. Reduced tillage minimizes the number of passes or the depth that is ploughed, while no-tillage (NT) aims to eliminate tillage completely and use a low-disturbance direct seeder. No-till leaves more than 30% of crop residues on the soil surface, while reduced tillage may leave 15-30% (Peigné et al., 2007). According to the 2009 census, an average of 28% of the total area seeded in Alberta, Saskatchewan and Manitoba was managed with reduced tillage, and 43% was managed with NT (Statistics Canada, 2007).

The benefits of conservation tillage to soil quality and crop performance are numerous and have been well documented. The organic mulch left on the soil surface increases surface SOM, which reduces soil erosion by promoting aggregate stability (Franzluebbers, 2002). Increased SOM reduces runoff and improves water-holding capacity and nutrient cycling, resulting in crop yield gains (Nielsen et al., 2002; Teasdale et al., 2007). In general microbial biomass and microbial diversity are increased under NT or reduced tillage systems as compared to conventional tillage (Holland, 2004; Lupwayi and Burr, 2010). Reducing tillage also lowers labour costs, energy consumption and carbon dioxide emissions, while increasing C sequestration (Holland, 2004; Lal, 2011).

2.2.2 Reduced tillage and organic agriculture

No-tillage and reduced tillage have been widely adopted in conventional agriculture, but are dependent on the use of herbicides for weed control. Organic producers have traditionally relied on tillage for nutrient management and weed control since the use of agrochemicals is strictly prohibited. Organic agriculture often employs many stages of tillage: deep ploughing to turn the soil; shallower tillage for seedbed preparation; and cultivation for weed control (Gliessman et al., 2007). Organic farmers are criticized for their heavy use of tillage, but organic production presents different challenges to reduced tillage as compared to conventional agriculture.

The same benefits of reduced tillage in conventional agriculture are likely applicable to organic agriculture in the long term; however, some effects of reduced tillage have negative impacts in the short term. Spring N mineralization is delayed without tillage to introduce oxygen and raise the soil temperature (Berner et al., 2008; Vaisman et al., 2011), and organic producers rely on mineralization – not synthetic N – to supply crop N uptake. An initial delay of crop growth in the spring results in decreased grain yield (Vaisman et al., 2011). The residue left on the surface under NT or reduced tillage management impedes the use of mechanical weeding equipment (Perron et al., 2001; Peigné et al., 2007; Teasdale et al., 2007), and weed pressure results in poor cash crop yields (Drinkwater et al., 2000; Peigné et al., 2007; Teasdale et al., 2007). Soil nutrient stratification associated with NT limits root access to available nutrients (Lupwayi et al., 2006b), which is difficult to ameliorate with organic amendments. Also, overall crop yield in organic agriculture is lower under NT management than conventional management (Drinkwater et al., 2000; Vaisman et al., 2011).

Benefits of reducing tillage (number of passes and depth) have been reported in some organic rotations. Use of chisel tillage instead of a mouldboard plough in Switzerland resulted in a 7.4% increase in soil organic C (SOC) after only three years (Berner et al., 2008). In the same experiment, maize (*Zea mays*) yields improved after six years of reduced tillage due to improved soil structure and moisture retention (Krauss et al., 2010). Reducing the number of tillage events for green manure termination from 4 to 2 resulted in profitable wheat yields and lower soil nitrate-N (Vaisman et al., 2011). Both environmental and economic sustainability can be increased in organic farms with the introduction of reduced-tillage strategies.

The main goal of reduced tillage is to increase SOM, which directly benefits organic systems since they rely on SOM to maintain soil fertility. Enhanced SOM levels and the associated benefits occur over a long period, and therefore organic growers may need to invest several years in reduced tillage before the benefits become apparent. Current research on reduced tillage in organics has focused on the green manure phase of rotations. Various researchers have explored alternative methods to replace tillage for green manure/cover crop termination in organics (Mischler et al., 2010; Smith et al., 2011; Vaisman et al., 2011).

2.3 Green Manures

Before the introduction of inorganic fertilizers, farmers relied on organic nutrients from animal or plant sources to replace the nutrients lost from their farms with harvest (Malhi et al., 2008). Due to the large size of farms on the prairies, the use of animal fertilizers is not practical, and most organic farmers rely on green manures or forage crops for soil nutrient management. Green manures are grown specifically to return plant biomass to the soil as an amendment. They are terminated while still green and incorporated or left on the surface as a mulch to decompose (Gliessman, 2007). Use of green manures can enhance soil quality and they are an important soil fertility maintenance strategy for sustainable agriculture (Fageria, 2007). The organic matter addition through green manuring improves soil physical, chemical, and biological properties as compared to summerfallow (Biederbeck et al., 1998, 2005). Use of green manures stimulates nutrient cycling through increased microbial activity (Wallace, 2001), microbial biomass (Lupwayi et al., 2004b), microbial populations (Biederbeck et al., 2005) and microbial diversity (Lupwayi et al., 2004b). Green manures also break insect, disease and weed cycles (Crookston et al., 1991).

The benefit of a green manure to the following crop is dependent on the green manure species, environmental conditions, and the management practices used. Desirable characteristics of a green manure are rapid growth and accumulation of biomass, ample nutrient uptake, adequate N_2 fixation of legume green manures, and minimal maintenance required during the growth period (Fageria, 2007). Because green manures are grown for the purpose of amending the soil, the nutrient contribution made to the system is of great interest. The N and P concentration of the crop and the decomposition rate will affect nutrient release from a green manure (Lupwayi et al., 2006a, 2007; Olson-Rutz et al., 2010). Generally, higher plant tissue N and P concentration and narrower C:N or C:P's results in net mineralization and soil nutrient availability. While beneficial to short-term nutrient availability, it is unlikely rapid nutrient turnover results in accumulation of SOM (Knight et al., 2010b). One of the difficulties with green manures is that unlike inorganic inputs that deliver readily available nutrients in a known amount, one must attempt to time the green manure termination for the proper decomposition and availability (Cherr et al., 2006).

On the Canadian prairies producers use annual, biennial or perennial green manures to manage soil fertility. In semi-arid regions, annual green manures are preferred because they use less soil moisture than biennial or perennial crops (Biederbeck and Bouman, 1994). Use of annual green manures requires a year out of production, and therefore the green manure must be managed properly to maximize the benefit.

2.3.1 Legume green manures

Legume green manures have the added benefit of producing plant-available N through biological N_2 fixation (BNF) from the atmosphere, and greatly improve the residue biomass quality. Legumes are also efficient at mobilizing P from the soil (Knight and Shirtliffe, 2005), and the stimulation of rhizosphere activity increases P uptake by other crops in the rotation (Johnston et al., 2008). The C:N:P ratios of legumes are narrow, which results in fairly rapid release of N and P from the residues (Lupwayi et al., 2006a, 2007).

Field pea (*Pisum sativum*) is an effective annual green manure. In an experiment of four green manures compared to continuous wheat or wheat-fallow in southern Saskatchewan, field pea returned the highest total dry matter, organic C and total N to the soil (Biederbeck et al., 1998). Field pea also had the highest dry matter production and average N yield of five legume green manures grown in Saskatoon, SK (Townley-Smith et al., 1993). These two previous studies were conventionally managed. A field experiment in Saskatoon, SK compared the differences in weed competition between ten field pea cultivars (Spies et al., 2011). The 40-10 forage pea was the only cultivar whose biomass stayed consistent in weed-free and weedy conditions, suggesting it was the most competitive of the ten cultivars. Weed biomass in the 40-10 field pea plots was three times lower than all of the other cultivars. Considering the weed-suppressing abilities of 40-10, it is recommended for use as an annual green manure in organic systems (Spies et al., 2011) and was chosen specifically for this study.

Limited research has been conducted on faba bean (*Vicia faba*) in organic systems. Nitrogen fixation rates for faba bean are reported to be higher than field pea and up to 350 kg N ha^{-1} (Rochester et al., 1998). One of the obstacles for its adoption has been the high cost of its large seed. The faba bean cultivar used in this study - CDC SSNS1 - was selected for smaller seed size (Oomah et al., 2011), making its use as a green manure more cost-effective. Faba bean is also known to be sensitive to moisture conditions, drought intolerant, and poorly competitive with weeds (De Costa et al., 2007; Hollinger, 2010).

2.3.2 Biological nitrogen fixation and natural abundance

Biological N_2 fixation is the process by which N_2 in the atmosphere is reduced to ammonia with the enzyme *nitrogenase* as a catalyst (Brady and Weil, 2002). Bacteria carry out BNF, and legumes are capable of fixing N_2 through a symbiotic relationship with *Rhizobium* bacteria in the soil. Bacteria infect the root hairs of the legume and eventually a root nodule is formed that is the active site of BNF (Brady and Weil, 2002). The legume supplies the bacteria with carbohydrates and the bacteria supplies N to the legume host.

Successful BNF is dependent on the formation of effective nodules on the roots, which is in turn dependent on the interaction of plant, soil and climatic factors (Fageria, 2007). The percent N derived from the atmosphere (%Ndfa) by a legume varies with legume and rhizobia species, environmental conditions, and crop management (Unkovich and Pate, 2000). A decrease in BNF is expected in soils with sufficient or excess N, pH lower than 6.5, moisture deficiency, or soils low in available P (Olson-Rutz et al., 2010). Biological N_2 fixation peaks at seed fill, and therefore early termination results in lower %Ndfa values.

There are several methods used to measure BNF. The ^{15}N natural abundance technique (Shearer et al., 1978) is suitable for use in organic systems because no N needs to be added to the soil, as in the ^{15}N dilution technique (Fried and Middleboe, 1977). The natural abundance method relies on the soil being naturally enriched in ^{15}N as compared to the atmosphere and compares the ^{15}N uptake of a non-legume with a N_2-fixing legume (Herridge et al., 2008). Because the atmosphere is less enriched in ^{15}N than the soil and the legume acquires part of its N from the atmosphere, the amount of dilution of the ^{15}N in the legume sample is proportional to the N_2 fixed (Shearer and Kohl, 1986). By comparing the ^{15}N in the legume with the ^{15}N in the reference crop, %Ndfa of the legume can be estimated.

2.3.3 Green manure intercrops

While legume green manures terminated early have narrow C:N's that provide N quickly to the system, a wider C:N may be more desirable for long-term soil fertility (Miller et al., 2011). Combining a legume with a non-legume (eg. cereal crop) widens the C:N and provides more biomass, creating a more resistant mulch that decomposes more slowly than a legume-only mulch (Morse and Creamer, 2006). A longer-lasting mulch suppresses weeds more effectively as compared to easily-degradable residue, and builds SOM. Research in the southern US determined mulches must produce at least 6000 kg ha^{-1} of biomass to control weed growth, and preferably over 8000 kg ha^{-1} (Morse and Creamer, 2006). The inclusion of a cereal in the green manure mixture is generally necessary to achieve such high biomass production. Decomposition and mineralization are slowed in the Canadian prairies as compared to the warmer regions of the southern United States, and therefore such high biomass production may not be necessary to achieve weed control. However, green manure intercrops have other benefits. A green manure crop with a range of C:N's can conserve N within the system (Drinkwater et al., 1998) and synchronize N release with crop uptake (Handayato et al., 1997). Non-legume green manures are more effective in depleting soil N, and therefore combining legumes and non-legumes maximizes N uptake (soil N + BNF) and reduces the risk of nitrate leaching (Rannells and Wager, 1997; Sainju et al., 1998). The increased C concentration in the intercrop residue should enhance SOM in the long-term as compared to legume-only residues.

While green manures are conventionally terminated with tillage, interest and research is growing in the area of surface-applied green manures that suppress weeds and lower evapotranspiration. To achieve maximize benefit from use of the roller-crimper, Vaisman et al. (2011) had to include a cereal with the legume green manure. Therefore, intercrop green manures may maximize the benefits of surface-applied residues as compared to legume-only residues.

2.4 Green Manure Termination Timing

Producers have been skeptical of the applicability of annual green manures in semiarid Saskatchewan due to soil moisture concerns. While legume N_2-fixation, N and P uptake, and biomass increase through flowering and pod fill (Olson-Rutz et al., 2010), green manures use more soil water the longer they grow and deplete soil moisture to the detriment of the subsequent crop. With proper management of termination timing, green manures in combination with snow trapping techniques could replace summerfallow in the semiarid prairies (Malhi et al., 2008). When terminating lentil green manure in the Brown soil zone of Saskatchewan at late flower in order to maximize BNF, Zentner et al. (2004) found that subsequent wheat yield decreased due to depleted soil moisture levels. When the study was adjusted to an earlier termination date (early flower) wheat yield following green manure was equivalent to or greater than wheat yield following summerfallow. Similarly, termination at early flower of spring and winter field pea green manure improved soil moisture reserves and subsequent wheat yields in Montana (Miller et al., 2006, 2008, 2011). In Saskatchewan it is recommended to seed green manures as early as possible in the spring, and terminate in early July (Zentner et al., 2004).

2.5 Green Manure Termination Method

The method employed to terminate a green manure affects nutrient cycling, soil moisture, and soil quality. Research into reduced tillage on organic farms has focused on the green manure phase because it is an integral part of most organic systems, and traditionally has relied heavily on tillage for incorporation (Drinkwater et al., 2000). Alternative methods for green manure termination are being explored that leave residue on the soil surface instead of incorporating it into the soil.

2.5.1 Tillage

Tillage with a tandem disc or mouldboard plough is the conventional method used for termination of green manures. On the Canadian prairies, farmers may pass over the green manure crop 3 or 4 times in summer and fall to achieve complete termination and to control weeds (Vaisman et al., 2011). Less than 30% of crop residues remain on the soil surface after incorporation by tillage, and it results in rapid mineralization of crop residues (Peigné et al., 2007). However, termination by tillage leaves the soil exposed from early or mid-July until the following spring, which leaves the soil susceptible to erosion and evapotranspiration. The rapid nutrient release from tilled residues may also result in asynchrony with crop uptake and losses through leaching or denitrification (Watson et al., 2002). Tillage also stimulates weed germination (Mohler, 2001; Blackshaw, 2005).

2.5.2 Rolling

The roller-crimper, also known as the blade roller, knife roller, and cover crop roller, is an implement used to terminate green manures or cover crops by laying the residue flat on the soil surface. Use of the roller-crimper (roller) originated in Brazil (Derpsch, 1991), but has been promoted by the Rodale Institute for NT organic production in North America, particularly for use with corn (*Zea mays*) and soybean (*Glycine max*) (Sayre, 2003). A roller consists of a hollow drum – that can be filled with water for extra weight – and blunted blades welded to the drum in a chevron shape (Figure 2.1) meant to ‘crimp’ the plant stems (Rodale Institute, 2010). The roller kills the plant tissue without cutting it and leaving a mulch anchored to the ground (Figure 2.2). It is a low-disturbance and energy efficient alternative to green manure termination by tillage, mowing, or herbicides.

Figure 2.1 The roller-crimper is depicted terminating a cover crop. The chevron blades ‘crimp’ the stems, killing the plant tissue and laying the mulch on the soil.
Source: http://www.nj.nrcs.usda.gov/about/2009Summary/2009_CTA.html

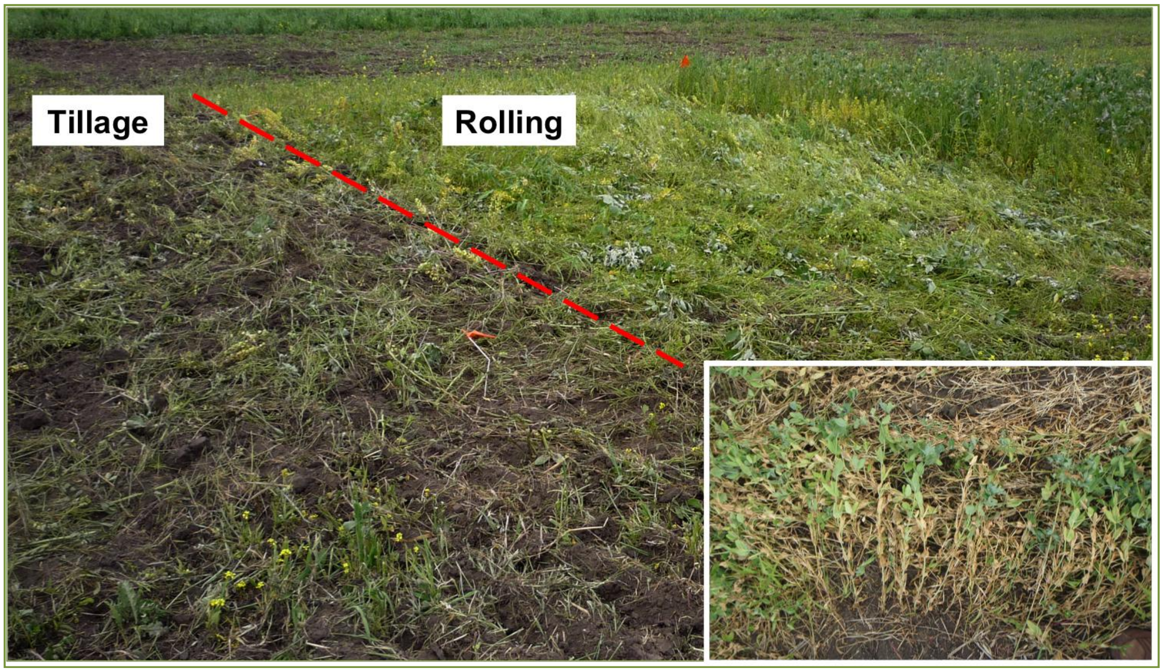

Figure 2.2 Photograph comparing green manure termination by tillage and rolling. Picture taken the day after termination at Kernen Research Farm, SK in 2009. The roller-crimper lays a green manure flat on the soil surface (inset).

The mulch laid down by the roller provides many advantages over other low-disturbance termination techniques. Because the plant stems are left intact the ground is more fully protected, reducing soil erosion, evapotranspiration, and weed germination. By rolling the residue in the direction of travel and leaving the roots anchored to the soil, direct seeding into the mulch is also greatly facilitated (Kornecki et al., 2009). Seeding directly into rolled residue eliminates tillage operations, which increases soil moisture retention and reduces erosion (Olson-Rutz et al., 2010). Use of the roller in a NT rye-soybean system required significantly less labour than the tilled system; return per hour of labour was estimated to be 25% greater in the NT system (Bernstein et al., 2011). Significant fuel reduction costs were also estimated (e.g. 720 L of diesel fuel per yr on an 18 ha organic farm). Rolling reduces fuel consumption and lowers machinery maintenance costs as compared to flail mowing (Creamer and Dabney, 2002), and can decrease costs by as much as \$26 ha^{-1} when compared to cover crop termination with herbicides (Ashford and Reeves, 2003).

Currently most research on use of the roller is being conducted in the southeastern US where corn is seeded directly into rolled hairy vetch (*Vicia villosa*) (Mischler et al., 2010), or soybean is seeded directly into rolled rye (*Secale cereale*) (Bernstein et al, 2011; Smith et al., 2011). Extensive research on tractor speeds, drum weight and configuration, and termination timing has been conducted to optimize the termination efficacy of the roller (Ashford and Reeves, 2003; Kornecki et al., 2006, 2009). The goals are to successfully terminate the crop (i.e. limit re-growth), suppress weeds, conserve moisture, and support a successful crop. Termination timing is important for successful crop kill; termination of a rye cover crop is more successful at late flower than early flower (Creamer and Dabney, 2002; Ashford and Reeves, 2003; Mirsky, 2009). Similarly, Mischler et al. (2010) reported variable control of hairy vetch with the roller through flowering stages, but kill was consistent after pod set. Termination timing also directly affects the biomass quality and quantity of a green manure, and soil properties. Generally, the later a green manure is terminated the more biomass it produces (resulting in a thicker mulch), the wider the C:N (slows decomposition), and the more soil water and nutrients the green manure uses. The last point is important to keep in mind when thinking of the effect on the following cash crop.

In the U.S., where the climate is warmer and wetter than the Canadian prairies, the goal is to create thick mulches that decompose slowly and permit direct seeding. On the cold, shortseasoned Canadian prairies a green manure is terminated in the summer and the field not seeded until the following spring. The concern in Canada is whether mineralization of residues left on the surface will be sufficient for the subsequent crop (S.J. Shirtliffe, personal communication, 2009). There is limited literature on low-till organic agriculture on the Canadian prairies. A study at the University of Manitoba was the first to examine spring wheat seeded into a green manure rolled in the previous season. Terminating a field pea/oat (*Avena sativa*) or field pea monocrop green manure by rolling resulted in significantly lower soil N and wheat yield than termination by tilling (Vaisman et al., 2011). As tillage was added to the rolling treatments N mineralization increased and N uptake and wheat yield responded positively. The combination treatment of rolled-twice and tilled-twice resulted in the same wheat yield but lower nitrate-N in the soil profile, which reduced the risk of leaching (Vaisman et al., 2011). Spring tillage was found to be critical for successful wheat establishment.

2.5.3 Mowing

Flail mowing is currently in use across the prairies for green manure termination, particularly for sweet clover (*Melilotus officinalis*) (Blackshaw et al., 2010). Because flail mowers are relatively accessible as compared to roller-crimpers, it was important to include mowing as a termination method for comparison. Mowing green manures offers a faster and less expensive termination method than tillage, and also reduces the risk of soil erosion (Blackshaw et al., 2010). However, mowing is more costly than rolling, and stimulates both weed and green manure re-growth (Kornecki et al., 2009). In contrast to rolling, which leaves the crop residue intact and anchored to the ground, mowing chops the residue into small pieces that are unevenly distributed across the soil surface and encourages weed germination (Creamer and Dabney, 2002). The small pieces of residue have a high surface area that is easily attacked by soil microorganisms, and therefore mowed mulches decompose more quickly than rolled mulches. Depending on the purpose of the mulch, faster decomposition may be beneficial, or detrimental to the cropping system. For example, in Saskatchewan where slow mineralization is a concern, an organic system could benefit from the faster mineralization rate as compared to rolling. In warmer climates with faster decomposition rates the intention is to maintain a thick mulch for weed suppression, and therefore a rolled mulch would be preferred (Smith et al., 2011).

2.6 Decomposition

All organic matter in the soil undergoes decomposition, which is largely carried out by soil microorganisms (Wolf and Snyder, 2003). The rate of decomposition and nutrient release from organic sources is a function of their chemical composition and physical form, soil and climate conditions, and cultural practices (Cookson et al., 2007). Generally young residues with narrow C:N's (<20:1) decompose quickly, as well as residues that are incorporated into the soil. Older materials with wider C:N's (>25:1) or those partly decomposed tend to decay more slowly, as do residues left on the soil surface (Wolf and Snyder, 2003). Decomposition is generally faster in warmer and wetter conditions, and slower in cold and dry regions (Chantigny et al., 2002; Henriksen and Breland, 1999). Soil oxygen is a key factor controlling decomposition rates because microorganisms require oxygen (Wolf and Snyder, 2003). Introducing oxygen into the soil through tillage is a common way to increase microbial activity.

As soil microorganisms decompose materials, N that was organically-bound becomes available for crop or microbial use (Lupwayi et al., 2006a). While C:N alone is not a perfect indicator of decomposition rate, it provides an idea of whether net N mineralization or immobilization will occur. A C:N <15:1 provides rapid release of plant-available N, while N in residues with a C:N of 25-40:1 is immobilized temporarily and released slowly (Olson-Rutz et al., 2010). Based solely on N content, if the N concentration in crop residues is < ~20 to 24 g N kg^{-1}, N will be immobilized instead of mineralized (Goos, 1995). Residues with lower N concentrations are immobilized because the microorganisms use the entire N supply for their own metabolism. Only when organic N exceeds microorganism demand is available N released into the soil (Crews and Peoples, 2005). Although narrow C:N's release more N in the short term, they do not contribute to the long-term organic N supply (Olson-Rutz et al., 2010).

In the cold, semi-arid region of Beaverlodge, AB, the percentage of residue N released from red clover (*Trifolium pratense*) green manure, field pea, canola (*Brassica rapa*) and monoculture wheat was positively correlated with residue N concentration and microbial activity, and negatively correlated with residue C:N (Lupwayi et al., 2006a). Nitrogen released in the first year was 71% from the red clover and 22% from the wheat, and the wheat treatment had the highest SOC in year one. In the first 5 weeks after residue placement, loss of N (mineralization) from decomposing green manures was faster under conventional tillage than under NT (Lupwayi et al., 2006). Another study in Beaverlodge reported increased loss of clover residue dry matter under conventional tillage (75%) than under NT (65%) after 12 months (Lupwayi et al., 2004a). While tillage increased mineralization of residues in the short-term, the green manure residues under NT had a higher percentage of recalcitrant N. Similarly, Recalcitrant N mineralizes slowly and increases soil fertility in the long-term (Miller et al., 2011).

2.7 Nitrogen in Organic Systems

Nitrogen is often the most yield-limiting factor in organic agriculture (Peigné et al., 2007). As mentioned previously, legume green manures or forage crops and mineralization of SOM are the most common sources of N used on organic farms in the prairies. A constant challenge in organics is ensuring there is an adequate supply of N, and that N release is synchronized with plant uptake. Prediction of nutrient supply from mineralization is difficult, but the slow release of N from decomposing green manures may be better synchronized with plant N uptake than inorganic N sources (Cherr et al. 2006). ‘Synchrony’ is what defines the relationship between N that feeds the world and N that harms the environment (Crews and Peoples, 2005). When N supply and demand does not match, N accumulates in the soil where it is at risk of being lost. Because N is very mobile, it can be lost from the soil through volatilization, leaching and denitrification. Reducing asynchrony in legume-based cropping systems can be accomplished through green manure management (termination timing, termination method, crop species, intercrops), but this required experimentation.

Immediate N contributions from green manures are generally low, but the residues contribute to the organic N pool and long-term fertility. In a field experiment using ^{15}N-labelled green manures, a spring wheat crop recovered only 14% of N from legume green manures the following year, compared to 36% of fertilizer N (Janzen et al., 1990). However, the green manures contributed twice as much to the organic N pool as the fertilizer treatments. Use of ^{15}N-labelled residues to determine N uptake can be misleading because newly added residues are immobilized by the microbial biomass, and unlabeled-N is mineralized and released (Crews and Peoples, 2005). This results in underestimating the N-supplying capacity of a green manure system.

Most of the legume-N remaining in the soil after green manure incorporation becomes part of the more active fraction of soil organic N, causing enhanced mineralization (Biederbeck et al., 2005). Mineralizable N (N_{min}) is an indicator of the future ability of a soil to supply N, and can be estimated in laboratory incubations. After four years of organic production N_{min} levels were higher as compared to a conventional NT system, even though soil nitrate levels were lower in the organic system (Miller et al., 2008). Considering that conventional soil tests tend to only measure soil NO_3, they are likely not the most useful soil tests for organic fields.

2.8 Phosphorus in Organic Systems

The amount of available P maintained naturally in soil solution is less than 0.1 mg L^{-1} because P is easily adsorbed and precipitated, or immobilized in microbial P (Conyers and Moody, 2009). For this reason conventional agriculture depends on the addition of chemical P for plant nutrition, but organic systems must rely on insoluble sources of P such as organic residues or rock phosphate. Organic producers must find ways to increase P availability through rotations or additions of easily mineralized materials high in P (Conyers and Moody, 2009). Maintaining crop residues in the system is important for P cycling, especially in organic system that are limited in available P (Entz et al., 2001). The average P level of nine organic farms surveyed in Saskatchewan, Manitoba and South Dakota was 15 kg ha^{-1} (Entz et al., 2001). Available soil P was deficient (<20 kg P ha^{-1}) at eight of the farms, and the farms with lowest P levels had been under organic management the longest. Soil samples (0 to 15 cm) collected from 60 organically-managed fields across Saskatchewan were determined to be deficient in available P (<34 kg ha^{-1}), indicating inevitable nutrient deficiencies with continued harvesting (Knight et al., 2010a). Standard soil-testing protocols were used and the results were compared to nutrient standards for conventional agriculture.

Legume green manures are efficient at mobilizing P from the soil (Knight and Shirtliffe, 2005). As green manures decompose, the P is released in a labile form that enhances the P nutrition of succeeding crops (Cavigelli and Thien, 2003). Organic acids released in the decomposition process aid in dissolving soil mineral P to improve crop uptake (Sharpley and Smith, 1989). Because soil microorganisms carry out mineralization of organic P, the rate and pattern are influenced by the same factors as organic N: residue quality and environmental factors. As with net N mineralization, net P mineralization is positively correlated with residue P concentration (Kwabian et al., 1987) and negatively correlated with C:P ratio (Hundal et al., 1987). However, extracellular enzyme phosphatase dominates P mineralization, and therefore C:P may be ineffective at predicting P mineralization. Generally, when P concentration in plant tissues is below 2 to 3 g P kg^{-1}, net P immobilization occurs (Yadvinder-Singh and Bijay-Singh, 1992). However, a pot study examining P uptake by sorghum (*Sorghum bicolor*) following perennial forages or green manures reported increased soil P following decomposition of forages with P concentration ~1 g kg^{-1} (Cavigelli and Thien, 2003). Sorghum P uptake was positively correlated with perennial forage P uptake, but no consistent relationship existed with green manure P uptake. Decomposition of the highest P containing green manure, lupin (*Lupinus albus*), actually resulted in the lowest sorghum P uptake (Cavigelli and Thien, 2003). These results suggest there are complex interactions involved in P uptake, and longer-term field studies are necessary to follow P interactions. Another pot study comparing wheat P uptake following field pea and faba bean green manure reported that faba bean has the greatest positive effect on wheat growth (Nuruzzaman et al., 2005). Faba bean P content (mg pot^{-1}) was twice as high as field pea P content, which the authors attributed to faba bean's large root system and ability to mobilize P.

As with N release, P mineralization from green manure residues increased under conventional tillage as compared to NT (Lupwayi et al., 2007).

2.9 Soil Quality and Soil Health

The concepts of soil quality and soil health go beyond productivity, and focus on how management practices affect the inherent capability of a soil to perform all of its functions. The terms lack official definitions because some researchers emphasize agricultural aspects, while others more environmental (Bastida et al., 2008). Soil quality was defined by Karlen et al. (1997) as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal health and habitation". Soil health has been defined as "the continued capacity of soil to function as a vital living system, within ecosystem or land-use boundaries, to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal and human health" (Doran et al., 1996). Soil quality is more related to soil function, while soil health is concerned with soil as a living resource. However, both emphasize the importance of sustaining soil for both agricultural productivity and environmental quality (Doran, 2002). The term 'soil quality' will be used in this dissertation. Soil quality is assessed based on biological, chemical and physical soil quality indicators and their interactions. Ideally, soil quality indicators should be fairly easy to measure under field conditions, sensitive to changes in management and climate, and associate well with ecosystem functions (Doran and Parkin, 1994).

2.9.1 Biological indicators of soil quality

Physical and chemical indicators of soil quality are of great importance agronomically and are fairly accessible to farmers; however, biological indicators are more sensitive to management changes (Bastida et al., 2008). Soil organic matter is a key biological indicator of soil quality due to its vital role in sustaining soil function and agroecosystem production. Among the essential services provided by SOM are the maintenance of soil structure, reduced soil erosion, increased water and nutrient storage, facilitation of decomposition, and C and N cycling (Malhi et al., 2010). Changes in SOM are difficult to measure in short- or medium-term studies, and therefore, indicators that respond to short-term changes in soil or crop management are preferred. Sensitive biological indicators of soil quality, such as microbial biomass and enzyme activity, provide insight into potential long-term effects of management practices (Doran, 2002), and have a shorter turnover rate (0.2 to 6 yr) than SOM (>20 yr) (Sparling 1997). These indicators of active organic matter are usually more informative for agronomic treatments than total SOM (Biederbeck et al., 2005).

2.9.2 Soil microbial biomass and soil quality indices

Soil microbial biomass is the “living component of SOM” (Jenkinson and Ladd, 1981) and is widely used as a soil quality indicator because it can reveal trends associated with management changes in 1 to 5 yr (Sparling et al., 1997). In addition to measuring total SMB, indices relating SMB and biochemical properties are used to assess soil quality. The microbial quotient (ratio of SMB-C to TOC) is a more sensitive index of soil change than SMB-C or SOM, and is considered an early indicator of TOC enhancement (Stockfish et al., 1999). Use of the microbial quotient also normalizes data from soils with varying TOC (Anderson and Domsch, 1989). Generally, SMB-C will decline faster than TOC when a soil is being exploited, and the microbial quotient decreases (Sparling, 1997). The ratio of SMB-C to SMB-N is an index used to monitor changes in the microbial community. Higher values reflect a higher proportion of fungi or older cells in the SMB relative to bacteria or younger cells (Joergensen et al., 1996).

Because organic producers recycle nutrients through the addition of organic matter and maintain diverse cropping systems, they inherently have higher SMB and diversity as compared to conventional systems (Stockdale and Watson, 2009). However, weed management achieved through intensive tillage decreases soil biological fertility, and can negatively impact soil quality. After 3 yr of reduced tillage intensity (chisel plough) in an organic system in Switzerland, SMB-C increased by 28% in the 0- to 10-cm depth and 6% in the 10- to 20-cm depth as compared to conventional tillage using mouldboard plough (Berner et al., 2008). In the same study, the microbial quotient increased by 15% at 0 to 10 cm under reduced tillage, and the SMB-C:SMB-N was 4% higher at 10 to 20 cm than the conventionally tilled soils. The SMB-C:SMB-N was equivalent between the tillage treatments at the 0- to 10-cm because a rototiller was used for weed control in both treatments, which disturbed the hyphal networks (Berner et al., 2008). Similarly, after 10 yr of reduced tillage intensity in an organic system, Emmerling (2007) reported increased SOC, SMB-C and SMB-N, microbial quotient and microbial activity at 0 to 15 cm in the layered ploughing as compared to mouldboard ploughing. The microbial quotient was reduced in the potato phase of an organic rotation in Nova Scotia, when the fields are more intensively tilled than a bean or carrot phase (Nelson et al., 2009). These results indicate reduced soil quality with intensive tillage. It was therefore of interest to examine the response of soil quality indicators as tillage was reduced in organic cropping systems on the Canadian prairies.

3. EFFECT OF GREEN MANURE CROP, TERMINATION TIMING AND TERMINATION METHOD ON SOIL N AND P AND CROP UPTAKE

3.1 Introduction

As with any export farming system, organic producers must find ways to replace the nutrients removed at harvest from their land. Soil fertility management is more challenging in organic agriculture because available soil inputs are limited by organic regulations. Unlike small-scale organic farms that can apply animal manures or organic soil amendments in a cost-effective manner, organic grain producers in Saskatchewan rely on crop selection and rotation, summerfallow, and green manures for nutrient management (Knight et al., 2010a). Producers in the Dark Brown and Black soil zones are encouraged to replace summerfallow with green manures and take advantage of the long-term benefits of green manuring: increased soil organic matter (SOM); improved soil structure; reduced soil erosion; and increased soil microbial activity (Wallace, 2001). Because the yield-limiting factors of organic production in Saskatchewan are soil fertility and precipitation, the green manure should be carefully selected and managed to maximize nutrient contribution and moisture retention in the system.

Legume green manures have increased benefits such as the ability to fix atmospheric N_2 and mobilize P from the soil (Knight and Shirtliffe, 2005). The nutrient contribution of a green manure to the subsequent crop will be reflected in its biomass and quality (C:N:P), which is determined by the N and P that a green manure is able to mobilize and uptake (Lupwayi et al., 2007). Desirable characteristics of legumes for use as annual green manures include: ability to fix large amounts of N_2 from the atmosphere (high percent N derived from atmosphere [%Ndfa]); high N and P uptake; conservation of soil moisture; and weed suppression/competition. Field pea (*Pisum sativum)* is an effective N_2-fixer and contributed high amounts of N to a green manure-spring wheat (*Triticum aestivum*) system in Swift Current, SK (Biederbeck et al., 1993, 1996, 1998). Field pea also had the highest dry matter production and average N yield of five green manures grown in the Dark Brown soil zone of Saskatchewan (Townley-Smith et al., 1993), and 40-10 field pea grows competitively in weedy environments (Spies et al., 2011). Faba bean (*Vicia faba*) was reported to fix up to 350 kg N ha^{-1} (Rochester et al., 1998) and contained double the P concentration in aboveground plant tissue as field pea in a greenhouse study (Nuruzzaman et al., 2005). In a conventional green manure-canola rotation, faba bean green manure consistently resulted in the highest canola yields (O'Donovan et al., 2011); however, limited research has been conducted on the use of faba bean as a green manure in organic systems. The disadvantages of faba bean are limited drought tolerance, poor competition with weeds, and high seed costs (Hollinger, 2010).

Termination timing of green manures is of interest because it directly influences soil moisture reserves, and the nutrient contribution a green manure makes to the system. One of the obstacles for adoption of annual green manures is concern of yield loss in the subsequent crop due to decreased soil moisture (Miller et al., 2006). Although the amount of N_2 fixed by a legume increases over the growing season through flowering and early pod (Zentner et al., 2004), in Saskatchewan it is recommended to terminate green manures at early flower to avoid moisture depletion for subsequent crops (Knight and Shirtliffe, 2005). At early flower, green manures also have a narrower C:N that allows for faster N mineralization (Bremmer and Van Kessel, 1992). To maximize soil moisture conservation green manures should be planted as early as possible in the spring, terminated by early to mid-July, and the residues managed to enhance snow-trapping (Biederbeck and Bouman; 1994; Zentner et al., 2004).

Green manure termination method also affects soil water use and nutrient cycling within a crop rotation. Green manures are usually terminated with one or several tillage events, which contribute to organic producers' heavy dependence on tillage for weed control and seedbed preparation (Drinkwater et al., 2000). With reduced tillage or no-tillage commonplace in conventional agriculture on the prairies, organic farmers are criticized for their excessive use of tillage. Excessive tillage can result in soil erosion (Beale et al., 1955), untimely N release due to rapid mineralization of crop residues or SOM (Lupwayi et al., 2006a), and the exposed soil is susceptible to moisture loss (Nielsen et al., 2002). Replacing tillage for green manure termination with alternative methods such as rolling or mowing could reduce the negative effects of tillage; however, the feasibility in organic systems remains uncertain.

The roller-crimper is being studied specifically to reduce tillage in the green manure phase of cropping systems. The roller-crimper is an implement that rolls over a crop and crimps the stems, killing the plant tissue and leaving a mulch anchored to the ground. Rolling or mowing green manures leaves the residues on the soil surface, helping to reduce evapotranspiration and trap snow (Ashford and Reeves, 2003; Kornecki et al., 2009; Olson-Rutz et al., 2010). However, leaving residues on the soil surface may decrease N mineralization and lower yields in the following crop (Mahli et al., 2010). Cultivation accelerates the mineralization of added residues by increasing the residue to soil contact and soil aeration (Lupwayi and Burr, 2010). The first study evaluating the roller in organic systems on the Canadian prairies found that eliminating tillage from a green manure-wheat cropping sequence resulted in low wheat yields as compared to termination by tillage (Vaisman et al., 2011). When rolling was combined with two tillage events, however, higher wheat yields were maintained. The focus of the present study, therefore, is not to eliminate tillage from the rotation, but to replace green manure *termination* with alternative implements, thereby *reducing* tillage in organic systems.

With limited research on reduced tillage in organic grain systems in Canada, the purpose of this study was to determine if a legume green manure could be terminated without incorporation and still sustain a high wheat yield the following year. The objectives were to: i) compare field pea and faba bean as annual green manures by measuring N_2-fixation, aboveground biomass, C:N, and N and P uptake at three termination times; ii) compare the soil N and P contributions of the two green manures in the first year, as affected by termination timing and termination method; and iii) determine the effect of field pea termination management (timing and method) on soil inorganic N and P, moisture, microbial biomass (SMB), and wheat N and P uptake in a green manure-wheat cropping sequence.

3.2 Materials and Methods

3.2.1 Site description

The field project was conducted in 2009 and 2010 at the Kernen Crop Research Farm (52°09’ N, 106°33’ W) near Saskatoon, SK and at an organic grain farm (52°19’ N, 106°5’ W) 50 km northeast of Saskatoon, near Vonda, SK. The Kernen soil is a Dark Brown Chernozem with a clay loam texture, and at Vonda a Black Chernozem with a sandy loam texture. Growing season temperatures in 2009 were lower than the long-term average (LTA), but similar to the LTA in 2010 (Table 3.1). Growing season precipitation was 30% lower at Kernen and 55% lower at Vonda than the LTA in 2009, and 150% higher at Kernen and 60% higher at Vonda in 2010 (Table 3.1). Both sites had been managed organically for over 10 years, and the experiments were established on land previously cropped to spring wheat. All plots were cultivated before seededing in May 2009. An initial soil sample was taken with a Dutch auger

Table 3.1 Mean monthly and crop year temperature, and total monthly and crop year precipitation during the 2009 and 2010 growing seasons at Kernen and Vonda (WeatherBug). The long-term averages (LTA) from 1971-2001 are included.

Research Site	Apr.	May	June	July	Aug.	Sept.	Oct.	Growing season†
Temperature (°C)								
Kernen 2009	1.9	6.1	15.9	14.6	16.0	15.4	1.3	13.2
Kernen 2010	6.5	10.0	16.0	17.8	16.4	10.5	7.1	15.1
LTA‡	4.7	11.8	16.0	18.3	17.6	11.5	4.8	15.9
Vonda 2009	1.6	8.5	15.4	15.4	15.9	16.2	1.1	13.8
Vonda 2010	6.3	9.8	15.8	17.7	16.2	10.1	6.4	14.9
LTA¶	6.0	11.2	15.0	17.9	18.1	12.4	4.3	15.6
Precipitation (mm)								
Kernen 2009	0.8	5.7	9.5	60.4	66.0	62.6	94.9	141.6
Kernen 2010	111.3	143.0	184.0	113.0	58.0	185.3	14.3	498.0
LTA	17.9	43.6	60.5	57.3	35.4	30.6	16.9	196.8
Vonda 2009	3.8	16.8	27.4	49.3	16.3	35.4	63.4	109.8
Vonda 2010	58.2	123.4	121.0	46.7	98.3	169.1	12.4	389.4
LTA	27.0	28.0	82.0	85.0	49.0	43.0	26.0	244.0

† Growing season is May to end of Aug.

‡ Long-term average from 1971-2001 for Saskatoon (52°09’ N, 106°36’ W) (Environment Canada).

¶ Long-term average from 1971-2001 for the nearest weather station to Vonda, SK, located at Osler, SK (52°4’ N, 106°5’ W) (The Weather Network).

(5 cm diameter x 15 cm depth) at depths of 0 to 15 and 15 to 30 cm at each site on 14 May 2009. Ten random samples were taken, composited by depth, mixed, and a subsample sent to ALS Laboratory Group Agricultural Services (Saskatoon, SK) for soil characterization (Table 3.2).

3.2.2. Experimental design

Year 1 (2009) of the experiment was the green manure treatment year, and Year 2 (2010) was the 'test' crop year where spring wheat was planted on all plots. The experiment was a three-way factorial trial: 1) green manure crop (field pea and faba bean); 2) termination method (rolling, mowing or tillage); and 3) termination timing (early flower, late flower or early pod). The experimental design was a randomized complete block design (RCBD) with four replicates. Individual plot size was 4 by 6 m. Plots were cultivated and then seeded to a green manure at a depth of 6 cm using a Fabro double-disc drill with 20-cm row-spacing. Field pea (cv. 40-10) and faba bean (cv. CDC SSNS1) were seeded at the recommended rates of 88 seeds m^{-2} (pea) and 44 seeds m^{-2} (faba bean) on 11 May at Vonda and 13 May at Kernen in 2009. Spring wheat microplots (3 rows, 1 m long) were seeded by hand (200 seeds m^{2}, 4-cm depth) within the treatment plots on 29 May 2009 as a non-N_2-fixing reference crop for use in the ^{15}N natural abundance method. Approximately two weeks after seeding the wheat microplots, the pea and faba bean plants, but not the weeds, were removed by hand from the microplots.

The 2009 green manure termination dates were 13 July (early flower), 22 July (late flower) and 5 August 2009 (early pod) at both Vonda and Kernen. Termination was accomplished with a single pass of a roller-crimper (rolling), flail mower (mowing), or tandem disc (tillage). All plots were cultivated at the end of October 2009 to control weeds and prepare the soil for spring seeding.

In May 2010, all plots were cultivated and then planted to spring wheat (cv. CDC Go) with a Fabro double-disc drill at a density of 250 seeds m^{-2} and 5-cm depth. The wheat was harrowed at the two-leaf stage to control weeds. Spring wheat was harvested on 26 August at Vonda and 31 August at Kernen with a small-plot combine.

Samples from the field pea plots were collected and analyzed in the green manure and wheat year of the experiment, while samples from the faba bean plots were only analyzed in the first year.

Table 3.2 Characterization of Kernen and Vonda soil from a composite soil sample taken in May 2009. Results reported by ALS Laboratory Group Agricultural Services (Saskatoon, SK).

Site	Depth	Texture	pH	EC†	NO_3-N	P	K	SO_4-S	Cu	Mn	Zn	B	Fe
	(cm)			mS cm^{-1}	------------ kg ha^{-1} ------------								
Kernen	0-15	clay loam	6.7	0.1	21.3	28.0	>600	10.1	1.1	25.0	3.4	2.6	88.5
	15-30		6.9	0.1	12.3	9.0	535.4	11.2	2.0	17.8	0.9	1.6	62.7
Vonda	0-15	sandy loam	8.3	0.3	24.6	>60	>600	>50	1.0	5.7	4.6	5.7	16.8
	15-30		8.6	0.2	12.3	51.5	>600	>50	1.1	5.2	1.5	3.5	22.4

† Electrical conductivity measured with 1:2 (soil:water).

3.2.3 Green manure year plant sampling and analysis

Green manure aboveground biomass was sampled by cutting all of the plant material at ground level from two 0.25 m^2 quadrats per plot on the day of termination. The plant samples were separated into green manure and weeds, dried at 70°C for several days, and the dry weights recorded. Aboveground biomass of five wheat plants from the middle row of each wheat microplot was harvested at ground level on the day of termination and dried at 70°C. Green manure re-growth and weed re-growth following termination were measured by Dr. Shirtliffe's staff in Plant Sciences (U of S); aboveground biomass was hand-harvested in mid-September. Figure 3.1 outlines the plant sampling in 2009 and 2010 at the sites.

Oven-dried green manure aboveground samples were ground to 2 mm with a Wiley Mill (Thomas Scientific, Swedesboro, NJ). A subsample was ball ground and retained for ^{15}N analysis (3.2.3.1). Total C and total N were analyzed by combustion using a LECO TruSpec Elemental Determinator (LECO Corporation, St. Joseph, MI). The C:N was calculated for the green manure samples.

Total N and P concentration ($\mu g\ g^{-1}$) of the green manure samples was determined by acid digestion (Thomas et al., 1967) and analysis with a SmartChem (Westco Scientific Instruments, Inc, Brookfield, CT). Green manure N and P uptake ($kg\ ha^{-1}$) were calculated according to Eq. [3.1]:

$$\text{N or P uptake } (kg\ ha^{-1}) = \frac{[\text{dry weight } (g\ m^{-2})] \times [\text{N or P concentration } (\mu g\ g^{-1})]}{10^5} \qquad [3.1]$$

Nitrogen uptake reported is a combination of N uptake from the soil and from biological N_2 fixation (BNF).

3.2.3.1 Biological N_2 fixation

Biological N_2 fixation of forage pea and faba bean was determined using the ^{15}N natural abundance method (Shearer et al., 1978), which is based on natural ^{15}N enrichment of the soil compared to the atmosphere (Herridge et al., 2008). This method compares the ^{15}N uptake of a non-legume with an N_2-fixing legume. The legume acquires part of its N from the atmosphere,

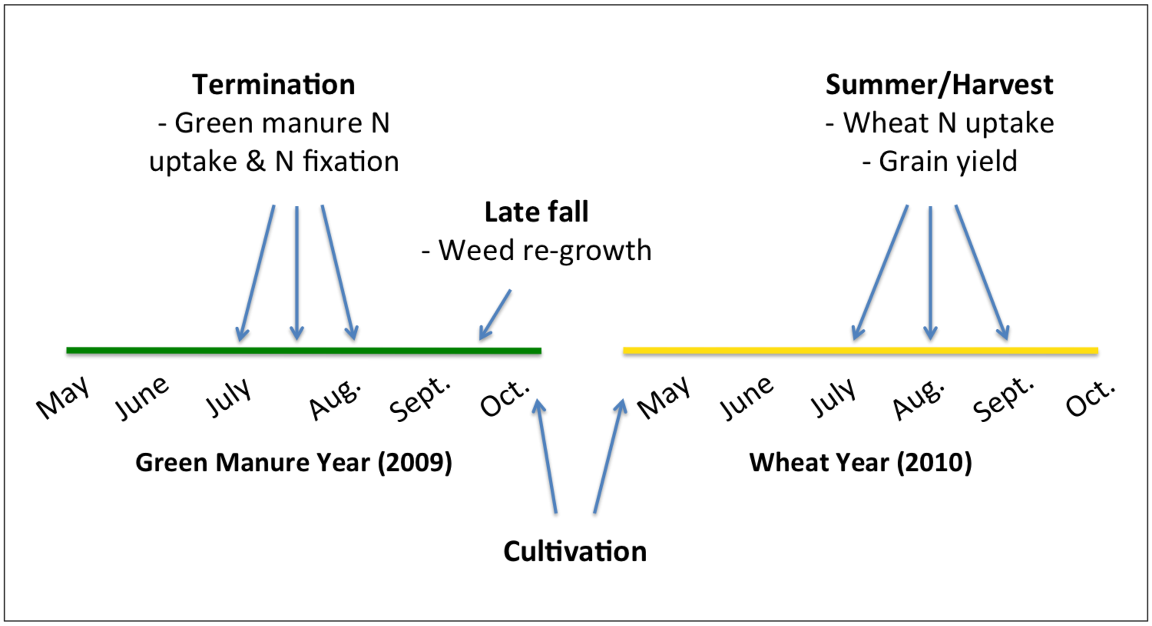

Figure 3.1 Plant sampling conducted at Kernen and Vonda throughout the experiment in 2009 and 2010. Only grain yield was measured on the September sample. All plots were cultivated in October 2009 and again in May 2010 before seeding wheat.

which is less enriched in ^{15}N than the soil, and therefore the amount of dilution of the ^{15}N in the sample is proportional to the N_2 fixed (Shearer and Kohl, 1986).

Wheat sampled from the microplots at termination was used as the non-fixing reference plant. Wheat subsamples were dried at 70°C, ground to 2 mm with a Wiley Mill and then ball ground to a fine powder. Wheat samples and aboveground green manure biomass samples (see above) from only the tilled treatments of the three termination times were analyzed on a Costech ECS4010 elemental analyzer (Costech Analytical Technologies Inc., Valencia, CA) coupled to a Delta V Advantage mass spectrometer with Conflo IV interface (Thermos Scientific, Bremen, Germany) to determine the δ^{15}N value. The samples were taken before termination; therefore, termination method is unimportant but termination time was compared. The percent N derived from the atmosphere (%Ndfa) of field pea or faba bean was determined according to Eq. [3.2]:

$$\%\mathrm{Ndfa} = \frac{(\delta^{15}\mathrm{N}_{\mathrm{Ref}} - \delta^{15}\mathrm{N}_{\mathrm{Fix}})}{\delta^{15}\mathrm{N}_{\mathrm{Ref}}} \times 100 \qquad [3.2]$$

where, $\delta^{15}N_{Ref}$ refers to the wheat plant and $\delta^{15}N_{Fix}$ refers to the legume green manure.

3.2.4 Green manure year soil sampling and analysis

Soil samples were taken approximately one week before each green manure termination date using a 4-cm diam. Dutch auger or 3.5-cm diam. backsaver probe (Table 3.3). Two 0- to 15- and 15- to 30-cm samples were taken from each plot and composited by depth. These samples were stored field moist in plastic bags at 4°C until analyses were performed. Soil was sampled again in October of 2009 prior to late-fall cultivation. A punch truck was used to take one 4-cm diam. core from each plot. The core was divided into 0- to 15-, 15- to 30- and 30- to 60-cm increments. At Vonda, a buried gravel layer prevented sampling deeper than 45 cm. The last increment was 30 to 45 cm.

A surface sample of 0 to 5 cm was taken from selected treatments for microbial biomass determination. The field pea treatments terminated at early flower and early pod by rolling or tillage were selected as the most likely to show differences in microbial biomass (4 treatments x 4 reps = 16 plots). Three samples were taken from each selected plot and combined. All of the samples were kept field moist at 4°C until analyses were performed. Following fall plant and soil

Table 3.3 Dates, depths and intended analyses of soil samples taken at Kernen and Vonda throughout the experiment in 2009 and 2010.

Study year	Sample time	Analysis	Date		Depth (cm)
			Kernen	Vonda	
Green manure year 2009	Early flower pre-term.	soil N, moisture	13 July	6 July	0-15, 15-30
	Late flower pre-term.	soil N, moisture	20 July	20 July	0-15, 15-30
	Early pod pre-term.	soil N moisture	29 July	29 July	0-15, 15-30
	Late fall	soil N, P, moisture	14/15 Oct.	15/16 Oct.	0-15, 15-30, 30-60[†]
		microbial biomass			0-5
Wheat year 2010	Spring	microbial biomass	NS[‡]	12 May	0-5
	Late fall	soil N, moisture	12 Oct.	10 Oct.	0-15, 15-30, 30-60, 60-90

† At Vonda soil could only be consistently sampled to 45 cm due to a buried gravel layer.

‡ NS = not sampled (Due to high rainfall Kernen was inaccessible for soil sampling in May 2010).

sampling, all plots were cultivated to kill remaining weeds. All of the soil sampling conducted throughout the experiment in 2009 and 2010 is outlined (Table 3.3).

Gravimetric soil moisture was determined on all soil samples by weighing 5 to 10 g moist soil, drying for 48 hours at 110°C, and then re-weighing. Gravimetric soil moisture was calculated according to Eq. [3.3]:

$$\text{Gravimetric soil moisture (\%)} = \frac{\text{wet soil} - \text{dry soil}}{\text{dry soil}} \text{ X } 100 \qquad [3.3]$$

Soil NO_3^- and NH_4^+ of all soil samples in May and August were extracted with 2.0 *M* KCl (Maynard et al., 2008): 5 g of field moist soil was shaken with 50 mL 2.0 *M* KCl for 1 hr at 142 rpm on a rotary shaker, then filtered through VWR 454 filter paper (VWR International). Soil PO_4 was extracted by the modified Kelowna procedure (Ashworth and Mrazek, 1995): 3 g of dried soil was shaken with 30 mL Kelowna solution for 5 min at 160 rpm, then filtered through VWR 454 filter paper. All extracts were kept at 4°C until the concentrations were measured on a SmartChem autoanalyzer. Soil NO_3^- and NH_4^+ were summed and are referred to as “Inorganic N”.

3.2.4.1 Soil microbial biomass

The chloroform-fumigation-extraction method (Voroney et al., 2008) was used to measure SMB-C and SMB-N. Soils were removed from 4°C storage and sieved through a 2-mm sieve in preparation for pre-incubation. Field capacity (FC) was estimated using a saturated soil column. Soil was placed in a 5- by 15-cm plastic column that was closed at one end with cheesecloth, and then placed upright in a bucket of sand. The soil was saturated with water and the open end of the column covered with Parafilm®. After 48 h, three 10 g samples were taken from within the column and gravimetric soil moisture of the three samples was determined according to Eq. [3.3]. An average of the three samples was calculated.

Gravimetric soil moisture was determined for each 0- to 5-cm sample. Four 25-g dry weight equivalent subsamples of the sieved soils were weighed into 125 mL glass jars. All of the samples were adjusted to 60% FC by adding water, and then mixed. The glass jars were covered with Parafilm® and incubated at 25°C for 7 d to stabilize soil metabolism before fumigation (Voroney et al., 2008). The bottles were opened every 3 d to reintroduce oxygen into the system to prevent the development of anaerobic conditions, and to re-adjust moisture content. Two of the four subsamples were fumigated and the remaining were unfumigated controls.

Fumigation was carried out according to Voroney et al. (2008) in a desiccator attached to a vacuum pump, using ethanol-free chloroform ($CHCl_3$). One set of duplicates was fumigated in a vacuum-sealed desiccator for 1 to 2 min with 50 mL $CHCl_3$. The desiccator was left sealed and in the dark for 24 h after fumigation. After 24 h the samples were evacuated with air from the vacuum pump system five times to remove residual $CHCl_3$.

Fumigated and unfumigated samples were extracted with 50 mL 0.5 M K_2SO_4. After shaking the jars for 1 h the soil suspension was filtered through Whatman™ GF-934-AH filter paper (GE Healthcare UK, Buckinghamshire, UK). The unfumigated samples were extracted immediately after the fumigated set was put in the desiccator for fumigation, and the fumigated samples were extracted after the 24 h fumigation period. The filtrate was frozen at -20°C until ready to analyze total organic C (TOC) and total N (TN) on a TOC-V modular machine (Shimadzu Corporation, Kyoto, Japan). Total organic C was analyzed on the TOC-V_{CPN} total organic C analyzer, and TN on the NTM-1 total N measuring unit (Shimadzu Corporation, Kyoto, Japan). The filtrates were diluted 50 times before analysis because the TOC-V is sensitive to high salt concentrations. Microbial biomass was determined according to Eq. [3.4] and [3.5]:

$$\text{SMB-C} = \frac{\text{TOC in fumigated samples} - \text{TOC in control samples}}{k_{\text{EC}}} \qquad [3.4]$$

$$\text{SMB-N} = \frac{\text{TN in fumigated samples} - \text{TN in control samples}}{k_{\text{EN}}} \qquad [3.5]$$

where $k_{EC} = 0.35$ and $k_{EN} = 0.5$ (Voroney et al., 2008) and are constants representing the efficiency of the extraction procedures.

3.2.5 Wheat year plant sampling and analysis

Wheat aboveground biomass samples were harvested in July and August to measure nutrient uptake. At each sampling time, two 50-cm rows of wheat plants were hand-harvested at ground level from random locations within each plot and then combined to make one sample per plot. The samples were dried at 70°C for several days, the dry weights recorded, and the samples ground to 2 mm with a Wiley Mill. Total N and P concentration (μg g^{-1}) were determined through acid digestion (Thomas et. al, 1967) and analysis with a SmartChem. Wheat N and P uptake (kg ha^{-1}) were calculated according to Eq. [3.1].

At harvest two 0.25 m^2 quadrats of aboveground biomass were harvested at ground level from each plot, dried at 70°C and threshed. The two quadrats per plot were threshed together and the resulting straw and seed weighed. Harvest index (%) was calculated according to Eq. [3.6]

$$\text{Harvest index (\%)} = \frac{\text{harvest seed weight (g)}}{\text{harvest seed+straw weight (g)}} \times 100\% \qquad [3.6]$$

Nitrogen and P content (μg g $seed^{-1}$) in the wheat seed was determined by acid digestion as described above. Grain protein content was calculated by multiplying %N by 5.7 (Williams et al., 1998).

3.2.6 Wheat year soil sampling and analysis

Selected treatments for SMB-C and SMB-N determination were sampled in May 2010 to 5 cm as described in the green manure year soil sampling. Only those plots that had grown field pea and were terminated at early flower and early pod by rolling or tillage were sampled. A final soil sample was taken in October 2010 using a punch truck to take one 4-cm diam. core from each plot. The core was divided into 0- to 15-, 15- to 30-, 30- to 60-, and 60- to 90-cm increments. Sampling to 90 cm at Vonda in 2010 was possible due to the high soil moisture content. All samples were kept field moist in plastic bags at 4°C until analyzed.

Gravimetric soil moisture, inorganic N and P on all soil samples, and microbial biomass for the 0- to 5-cm subset were analyzed as described for the green manure year.

3.2.5 Statistical methods

Data was analyzed as a 3- or 2-way randomized complete block design using ANOVA in CoStat (CoHort Software, Monterey, CA). Green manure crop, termination method and termination timing were the effects. When field pea and faba bean were being compared, the data was analyzed as a 3-way ANOVA with green manure crop as an effect. Because faba bean established poorly and did not function properly as a green manure, only the effects of field pea were followed through the entire green manure-wheat cropping sequence. When field pea alone was analyzed, a 2-way ANOVA was used with termination method and termination timing as effects. Main effects and their interactions were considered significant at $P<0.05$. Variables were checked for normality; no transformations were necessary. The two sites were analyzed separately due to inherent differences in soil properties. When sample sizes (n) were equivalent, means within treatments were compared using Tukey's HSD at the 5% level of significance. When n was uneven due to a missing sample, means were compared using Tukey-Kramer at the 5% level of significance. Tukey-Kramer was used for Kernen and Vonda fall 2009 inorganic N and P (total profile), Vonda field pea treatment fall 2010 inorganic N and P (60 to 90 cm and total profile), and Vonda wheat harvest measurements.

Correlations were run between %Ndfa of field pea or faba bean and soil properties at termination (soil moisture and soil inorganic N) at Kernen and Vonda using CoStat. The Pearson Product Moment Correlation Coefficient (r) was used to measure the linear association between the factors, and a linear relationship was considered significant at $P<0.05$.

3.3 Results

3.3.1 Green manure quality

Faba bean did not establish well at either site in the experiment (Figure 3.2), and failed as a green manure crop due to its extremely low biomass. Field pea biomass was 2 to 5 times greater than that of faba bean, depending on the termination stage. At Kernen, a high infestation of blister beetles damaged the stems and flowers of faba bean (Figure 3.3).

Kernen

Crop and termination timing significantly affected the green manure characteristics measured at Kernen (Table 3.4). Field pea's average biomass of 2485 kg ha^{-1} was 65% greater than faba bean's biomass (864 kg ha^{-1}), which resulted in higher N and P uptake for field pea (Table 3.5). Faba bean had a higher N and P concentration and a much narrower C:N than field pea. Green manure biomass, C:N, and N and P uptake increased from early flower to early pod for both crops; and N content decreased at early pod (Table 3.6). There was an interaction

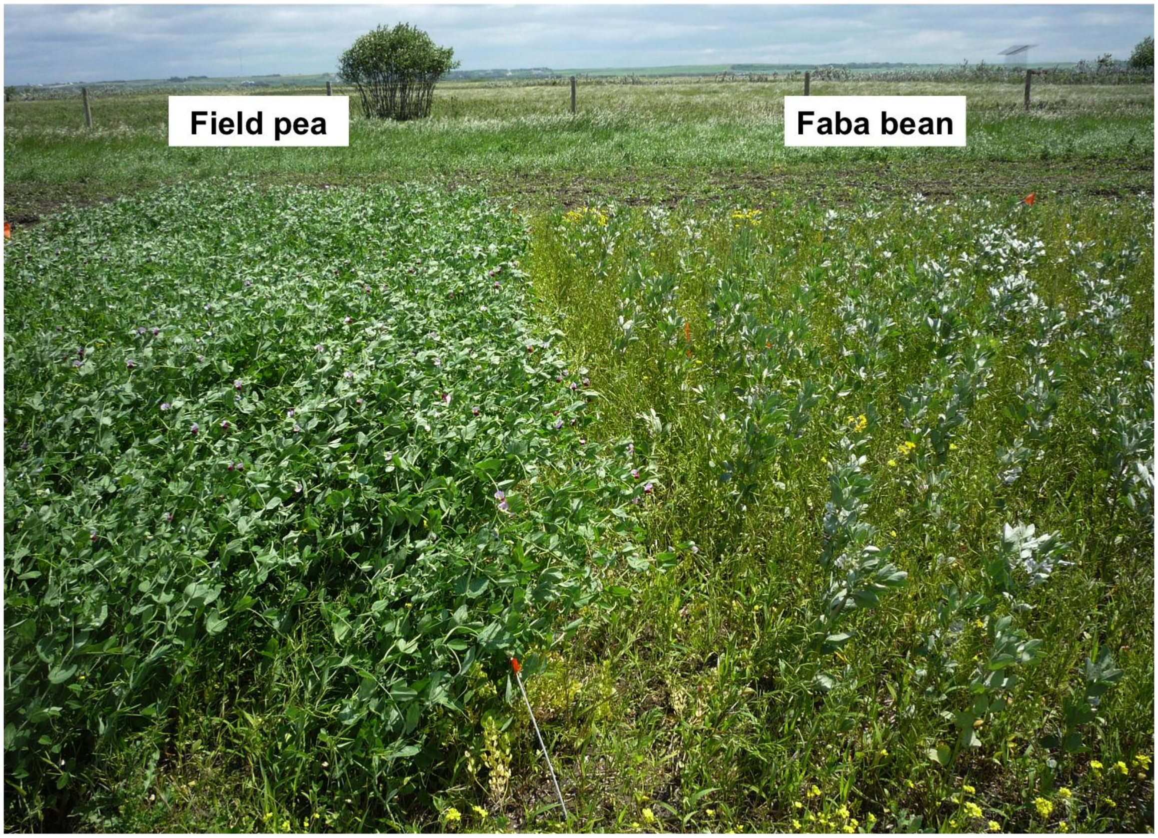

Figure 3.2 Established field pea and faba bean green manure plots at Kernen. Photograph taken 30 d after seeding.

Figure 3.3 Blister beetles feeding on the blossoms of faba bean plants on 13 July 2009 at Kernen (left). Damaged faba bean 29 July 2009 at Kernen (right).

Table 3.4 Probability levels from the three-way analysis of variance for green manure management effect on green manure biomass, nutrient concentration, and nutrient uptake at **Kernen** in 2009. Source of variation of two crops (C), three termination methods (TM), and three termination times (TT) considered significant at $P < 0.05$.

Source of variation	df[†]	Biomass	C:N	N conc.	P conc.	N uptake	P uptake
		---------- Probability (P) ----------					
C[‡]	1	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
TM[§]	2	0.3407	NA[¶]	0.4273	0.9200	0.5661	0.4538
TT[#]	2	**<0.0001**	**0.0012**	**<0.0001**	**0.0016**	**<0.0001**	**<0.0001**
C x TM	2	0.1598	NA	0.6563	0.3865	0.2963	0.4545
C x TT	2	0.8162	0.2158	0.0647	**0.0107**	0.5241	0.5734
TM x TT	4	0.8550	NA	0.2939	0.4711	0.7543	0.4190
C x TM x TT	4	0.6943	NA	0.3212	0.7339	0.6057	0.5790

† Degrees of freedom.

‡ Crops were field pea and faba bean.

§ Termination methods were rolling, mowing and tillage.

¶ NA = not analyzed.

Termination timings were early flower, late flower and early pod.

Table 3.5 Mean biomass, C to N ratio, nutrient concentration, and nutrient uptake of field pea and faba bean green manures measured at Kernen and Vonda in 2009.

Site	Green manure	Biomass	C:N	N conc.	P conc.	N uptake[†]	P uptake
	n=12	kg ha^{-1}		---------- g kg^{-1}	------	kg N ha^{-1}	kg P ha^{-1}
Kernen	Field pea	2484.9a[‡]	23b	18.3b	1.6b	44.0a	3.8a
	Faba bean	863.8b	15b	27.0a	2.7a	21.9b	2.0b
Vonda	Field pea	2520.1a	16a	27.8	3.1b	68.0a	7.6a
	Faba bean	1003.4b	16a	28.6	4.0a	27.4b	3.7b

† N uptake is a combination of N uptake from soil and N_2 fixation.

‡ Means in the same column and within a site followed by different letters are significantly different at $P<0.05$ according to Tukey's HSD.

Table 3.6 Mean green manure (field pea & faba bean) biomass, C to N ratio, nutrient concentration, and nutrient uptake for three different termination times at Kernen and Vonda in 2009.

Site	Termination timing	Biomass	C:N	N conc.	P conc.	N uptake[†]	P uptake
	n=12	kg ha^{-1}		---------- g kg^{-1}	------	kg N ha^{-1}	kg P ha^{-1}
Kernen	Early flower	969.5b[‡]	23b	23.9a	2.3a	19.6b	1.7b
	Late flower	1765.8a	27ab	23.9a	2.1ab	36.7a	3.1a
	Early pod	2287.6a	29a	20.2b	1.9b	42.6a	3.9a
Vonda	Early flower	826.5b	14b	30.6a	4.0a	24.2b	2.8b
	Late flower	2149.8a	14b	30.8a	3.6b	65.4a	7.5a
	Early pod	2308.9a	18a	23.2b	3.1c	53.5a	6.6a

‡ N uptake is a combination of N uptake from soil and N_2 fixation.

† Means in the same column and within a site followed by different letters are significantly different at $P<0.05$ according to Tukey's HSD.

between crop and termination timing for green manure P content; P content was the same for all termination times in field pea (1.6 g P kg^{-1}), but decreased from 3.1 g P kg^{-1} at early flower to 2.3 g P kg^{-1} at early pod in faba bean (data not shown).

Vonda

At Vonda, termination timing had a significant effect on all of the measured green manure characteristics, and crop had a significant effect on all but C:N and N concentration (Table 3.7). Average faba bean biomass (1003 kg ha^{-1}) was 40% of field pea biomass (2520 kg ha^{-1}) and resulted in higher N and P uptake for field pea (Table 3.5). Termination at early flower resulted in lowest green manure biomass and N and P uptake, while N and P concentration was lowest when terminated at early pod (Table 3.6). There was an interaction between crop and termination time for green manure C:N (Table 3.7), but it was inconsequential. Carbon to N ratio was highest at early pod for both field pea (18:1) and faba bean (19:1) (data not shown). Termination timing affected P concentration differently depending on the green manure at Vonda. Phosphorus concentration of field pea was equivalent at early and late flower (3.3 g kg^{-1}), and lower at early pod (2.8 g kg^{-1}); P content for faba bean was equivalent at late flower and early pod (3.6 g kg^{-1}), and higher at early flower (4.7 g kg^{-1}) (data not shown).

3.3.2 Nitrogen fixation

Kernen

Averaged across all termination times, there was no difference in %Ndfa between field pea and faba bean at Kernen (Table 3.8). Mean amount of N fixed ha^{-1} was significantly higher for field pea (36.2 kg N ha^{-1}) than faba bean (14.8 kg N ha^{-1}), and tended to be lowest at early flower for both crops (Table 3.8). There were no significant differences between termination timing for %Ndfa at Kernen averaged across both crops (data not shown). Early flower termination resulted in lower %Ndfa for faba bean than later termination timings (Table 3.8).

There were no correlations between soil properties at termination and %Ndfa of field pea or faba bean at Kernen.

Table 3.7 Probability levels from the three-way analysis of variance for green manure management effect on green manure biomass, nutrient concentration, and nutrient uptake at **Vonda** in 2009. Source of variation from two crops (C), three termination methods (TM), and three termination times (TT) considered significant at *P*<0.05.

Source of variation	df[†]	Biomass	C:N	N conc.	P conc.	N uptake	P uptake
		Probability (*P*)					
C[‡]	1	**<0.0001**	0.8762	0.2769	**<0.0001**	**<0.0001**	**<0.0001**
TM[§]	2	0.7147	NA[¶]	0.1370	0.3333	0.4308	0.5125
TT[#]	2	**<0.0001**	**<0.0001**	**<0.0001**	**0.0016**	**<0.0001**	**<0.0001**
C x TM	2	0.9228	NA	0.7323	0.7057	0.8075	0.8761
C x TT	2	0.0998	**0.0085**	0.0870	**0.0157**	0.2061	0.3369
TM x TT	4	0.6541	NA	0.2266	0.8764	0.2761	0.3830
C x TM x TT	4	0.8591	NA	0.9553	0.4888	0.8260	0.8343

† Degrees of freedom.
‡ Crops were field pea and faba bean.
§ Termination methods were rolling, mowing and tillage.
¶ NA = not analyzed.
# Termination timings were early flower, late flower and early pod.

Table 3.8 Mean values of percent N derived from the atmosphere (%Ndfa) and N fixed for each green manure crop and three termination times at Kernen and Vonda in 2009.

		Green manure N_2 fixation			
Green manure	Termination timing	Kernen		Vonda	
		Ndfa	N fixed	Ndfa	N fixed
	n=4	%	kg N ha^{-1}	%	kg N ha^{-1}
Field pea	Early flower	65[†]	23.4	70	**32.4b**
	Late flower	79	44.0	84	**75.7a**
	Early pod	66	41.2	89	**57.0ab**
Average[‡]		*70*[¶]	***36.2a***	*81*	***55.0a***
Faba bean	Early flower	**46b**	3.6	66b	8.0
	Late flower	**73a**	14.1	84a	37.8
	Early pod	**76a**	26.6	89a	23.5
Average		*65*	***14.8b***	*79*	***23.1b***

† Means in the same column and within a green manure crop followed by different letters and bolded are significantly different at $P<0.05$ according to Tukey's HSD; means in the same column and within a green manure crop not followed by letters are not significantly different.
‡ Average value across all termination times for field pea or faba bean are in italics.
¶ Average values within a column followed by different letters and bolded are significantly different between green manure crop species at $P<0.05$ according to Tukey's HSD; averages within a column not followed by letters are not significantly different.

Vonda

Percent Ndfa at Vonda was similar between field pea (81%) and faba bean (79%), but field pea fixed more N than faba bean (Table 3.8). Averaged across both crops, %Ndfa was lowest at early flower termination (data not shown), and was significantly lower at early flower for faba bean. Fixed N values were highest at late flower and lowest at early flower for field pea, and tended to be highest at late flower for faba bean (Table 3.8).

Faba bean %Ndfa was negatively correlated with 0 to 15 cm soil inorganic N (r = -.066, P=0.0199) and soil moisture (r = -0.71, P=0.0098) at termination at Vonda.

Mean %Ndfa and fixed N were higher at Vonda (80%, 39.1 kg N ha^{-1}) than Kernen (67%, 25.5 kg N ha^{-1}).

3.3.3 Green manure year soil data

3.3.3.1 Field pea and faba bean

Kernen

Green manure crop and termination timing influenced soil moisture and inorganic N (0 to 15 cm) measured at termination (Table 3.9). Growing field pea resulted in lower soil moisture and higher soil inorganic N at termination than growing faba bean (Table 3.10). Soil moisture at termination decreased significantly with each termination date: from 22% at early flower down to 12% at early pod (Table 3.10). The estimated FC (33 kPa) at Kernen, based on a clay loam texture and 2.5% organic matter, was 36% (Saxton and Rawls, 2006). Inorganic N also decreased with termination timing, and dropped significantly from 30.5 kg ha^{-1} at early flower to 9.0 kg ha^{-1} at early pod (Table 3.10).

Fall moisture was unaffected by treatment; while total inorganic N (0 to 60 cm) measured in the fall was affected by crop and termination timing (Table 3.9). Furthermore there was a crop by termination timing interaction for inorganic N to 60 cm in the fall. Mean inorganic N to 60 cm was highest for field pea and also at early pod (Table 3.10). Field pea terminated with rolling resulted in the highest fall inorganic N and tillage the lowest, but termination by tillage had the highest inorganic N for faba bean (Figure 3.4). Total profile PO_4 was greater in the plots that had grown field pea than faba bean (Table 3.10).

Table 3.9 Probability levels from the three-way analysis of variance for green manure management effect on soil moisture, soil available N and P at **Kernen** in 2009. Source of variation of two crops (C), three termination methods (TM), and three termination times (TT) considered significant at P<0.05.

Source of variation	df[†]	Moisture at term[‡] (0-15cm)	Inorganic N at term (0-15cm)	Fall moisture (0-15cm)	Fall inorganic N (0-60cm)	Fall PO_4 (0-60cm)
		---------------------------- Probability (P)				-------------------------------
C[§]	1	**0.0220**	**0.0438**	0.7078	**0.0029**	**0.0421**
TM[¶]	2	0.0898	NA[#]	0.9986	0.8387	0.2692
TT[††]	2	**<0.0001**	**<0.0001**	0.5694	**0.0196**	0.5956
C x TM	2	0.8484	NA	0.5531	**0.0022**	0.7296
C x TT	2	0.9024	0.3852	0.7050	0.8649	0.9441
TM x TT	4	0.1585	NA	0.8450	0.0418	0.2002
C x TM x TT	4	0.5556	NA	0.3369	0.3595	0.8303

† Degrees of freedom.

‡ term = samples taken immediately prior to green manure termination.

§ Crops were field pea and faba bean.

¶ Termination methods were rolling, mowing and tillage.

NA = not analyzed.

†† Termination timings were early flower, late flower and early pod.

Table 3.10 Effect of green manure crop, termination timing and termination method on soil moisture, inorganic N and P at green manure termination and in the fall following termination at **Kernen** in 2009.

Factor	Treatment	Moisture at term[†] (0-15cm)	Inorganic N at term (0-15cm)	Fall moisture (0-15cm)	Fall inorganic N (0-60cm)	Fall PO_4 (0-60cm)
		---- % ----	kg N ha^{-1}	---- % ----	kg N ha^{-1}	kg P ha^{-1}
Crop	Field pea	**16.4b**[‡]	**23.4a**	32.6	**29.0a**	**56.9a**
n=36	Faba bean	**17.9a**	**19.2b**	32.2	**23.5b**	**51.4b**
Termination	Rolling	16.2	NA[§]	32.4	27.3	57.1
method	Mowing	17.4	NA	32.4	25.6	52.1
n=24	Tillage	17.9	NA	32.3	26.0	53.3
Termination	Early flower	**21.5a**	**30.5a**	31.8	**27.4ab**	56.0
timing	Late flower	**17.8b**	**24.4a**	33.1	**22.7b**	52.8
n=24	Early pod	**12.3c**	**9.0b**	32.3	**28.9a**	53.7

† term = samples taken immediately prior to green manure termination.

‡ Means in the same column and within a factor followed by different letters and bolded are significantly different at *P*<0.05 according to Tukey's HSD; means in the same column and within a factor not followed by letters are not significantly different.

§ NA = not analyzed.

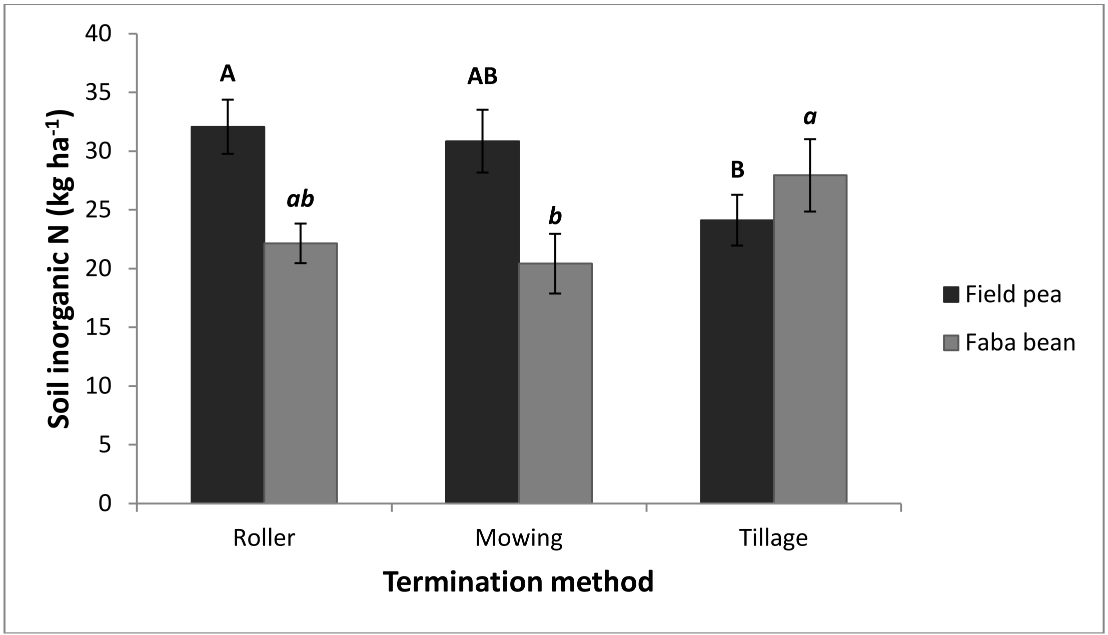

Figure 3.4 Soil inorganic N (NO_3^- + NH_4^+) throughout the 0- to 60-cm soil profile measured in the fall of 2009 at **Kernen**. Samples were taken at 0 to15-, 15- to 30-, and 30- to 60-cm increments and data combined for total profile N (0 to 60 cm). Crop by termination method interaction was significant (*P*=0.0022). Different letters within a crop species indicate significant differences between termination methods at *P*<0.05 according to Tukey's HSD. Bars indicate standard error of means (*n*=12).

Vonda

Green manure crop and termination timing affected soil moisture (0 to 15 cm) at Vonda (Table 3.11). The faba bean plots had 7.9% soil moisture while field pea plots had 7.5%, and soil moisture decreased significantly with termination date (Table 3.12). Field capacity (33kPa) at Vonda was estimated to be 18%, based on a sandy loam texture and 2.5% organic matter (Saxton and Rawls, 2006). Inorganic N (0 to 15 cm) at termination tended to decrease with termination date, and decreased significantly from 15.2 kg ha^{-1} at late flower to 7.6 kg ha^{-1} at early pod (Table 3.12).

Total inorganic N (0 to 45 cm) measured in the fall was greater for field pea than faba bean (33.8 and 27.6 mg kg^{-1} respectively) and was also affected by termination timing and method (Table 3.11). Fall inorganic N was significantly lower when terminated at early flower than late flower (Table 3.12), and the rolled plots had lower soil N than the tilled plots. Fall inorganic P was unaffected by the treatments.

3.3.3.2 Focus on field pea

More in depth soil results are shown only for field pea, since faba bean did not establish properly and hence did not perform as a green manure.

Kernen

Termination method affected soil inorganic N in samples taken in the late fall of 2009 before cultivation (Table 3.13). The rolled field pea treatment had significantly more inorganic N than the tilled treatment at the 15- to 30- and 0- to 60-cm depths, and plots terminated by rolling tended to have higher inorganic N across all soil depths (Table 3.13). Termination timing did not affect soil inorganic N.

Soil moisture (0 to 15 cm) measured in late fall was not affected by field pea green manure management (Table 3.13). Rolling field pea resulted in greater soil moisture conservation at the 15- to 30-cm depth than tilling field pea (23 and 19% respectively). Soil moisture at depth (30 to 60 cm) tended to decrease with termination date, and early flower termination had higher soil moisture than termination at early pod (Figure 3.5).

Table 3.11 Probability levels from the three-way analysis of variance for green manure management effect on soil moisture, soil available N and P at **Vonda** in 2009. Source of variation of two crops (C), three termination methods (TM), and three termination times (TT) considered significant at *P*< 0.05.

Source of variation	df[†]	Moisture at term[‡] (0-15cm)	Inorganic N at term (0-15cm)	Fall moisture (0-15cm)	Fall inorganic N (0-45cm)	Fall PO_4 (0-45cm)
		Probability (*P*)				
C[§]	1	**0.0470**	0.9355	0.4008	**0.0356**	0.8005
TM[¶]	2	0.2292	NA[#]	0.3408	**0.0274**	0.9576
TT[††]	2	**<0.0001**	**<0.0001**	0.2523	**0.0352**	0.3928
C x TM	2	0.1467	NA	0.0910	0.6925	0.6455
C x TT	2	0.6633	0.4065	0.8634	0.3970	0.3099
TM x TT	4	0.1588	NA	0.4465	0.0601	0.2022
C x TM x TT	4	0.0120	NA	0.3027	0.6146	0.3935

† Degrees of freedom.

‡ term = samples taken immediately prior to green manure termination.

§ Crops were field pea and faba bean.

¶ Termination methods were rolling, mowing and tillage.

NA = not analyzed.

†† Termination timings were early flower, late flower and early pod.

Table 3.12 Effect of green manure crop, termination timing and termination method on soil moisture, inorganic N and P at green manure termination and in the fall following termination at **Vonda** in 2009.

Factor	Treatment	Moisture at term[†] (0-15cm)	Inorganic N at term (0-15cm)	Fall moisture (0-15cm)	Fall inorganic N (0-45cm)	Fall PO$_4$ (0-45cm)
		---- % ----	kg N ha^{-1}	---- % ----	kg N ha^{-1}	kg P ha^{-1}
Crop	Field pea	**7.5b**[‡]	13.6	15.2	**33.8a**	166.3
n=36	Faba bean	**7.9a**	13.5	16.4	**27.6b**	161.7
Termination	Rolling	7.6	NA[§]	15.5	**25.4b**	163.5
method	Mowing	7.6	NA	16.9	**31.8ab**	167.6
n=24	Tillage	7.9	NA	15.0	**34.9a**	160.9
Termination	Early flower	**9.3a**	**17.9a**	16.5	**25.4b**	167.8
timing	Late flower	**7.9b**	**15.2a**	16.3	**34.2a**	152.4
n=24	Early pod	**5.9c**	**7.6b**	14.5	**32.5ab**	171.1

[†] term = samples taken immediately prior to green manure termination.

[‡] Means in the same column and within a factor followed by different letters and bolded are significantly different at $P<0.05$ according to Tukey's HSD; means in the same column and within a factor not followed by letters are not significantly different.

[§] NA = not analyzed.

Table 3.13 Mean soil inorganic N ($NO_3^- + NH_4^+$) and gravimetric soil moisture at different sample depths as affected by termination method of field pea green manure. Samples taken at **Kernen** in the fall of 2009 after green manure termination. ANOVA table showing probability level where effect of source of variation considered significant at $P<0.05$.

Termination method	Soil inorganic N				Soil moisture		
	Depth (cm)				Depth (cm)		
	0-15	15-30	30-60	0-60	0-15	15-30	30-60
n=12	--------------- kg N ha^{-1} --------------				-------------- % --------------		
Rolling	16.2†	**9.0a**	6.9	**32.1a**	33.1	**22.8a**	14.7
Mowing	15.0	**7.0ab**	8.0	**30.8ab**	32.8	**20.6ab**	15.4
Tillage	11.5	**5.9b**	6.7	**24.1b**	31.8	**18.6b**	16.7

Source of variation	------------------------------------Probability *(P)*----------------------------						
Termination method (TM)	0.1225	**0.0359**	0.5884	**0.0343**	0.8026	**0.0144**	0.2483
Termination timing (TT)	0.5075	0.2327	0.2955	0.1244	0.8265	0.3711	**0.0025**
TM x TT	0.1927	0.3924	0.7692	0.0835	0.8245	0.2138	0.6698

† Means within a column followed by different letters and bolded are significantly different at $P<0.05$ according to Tukey's HSD; means within a column not followed by letters are not significantly different.

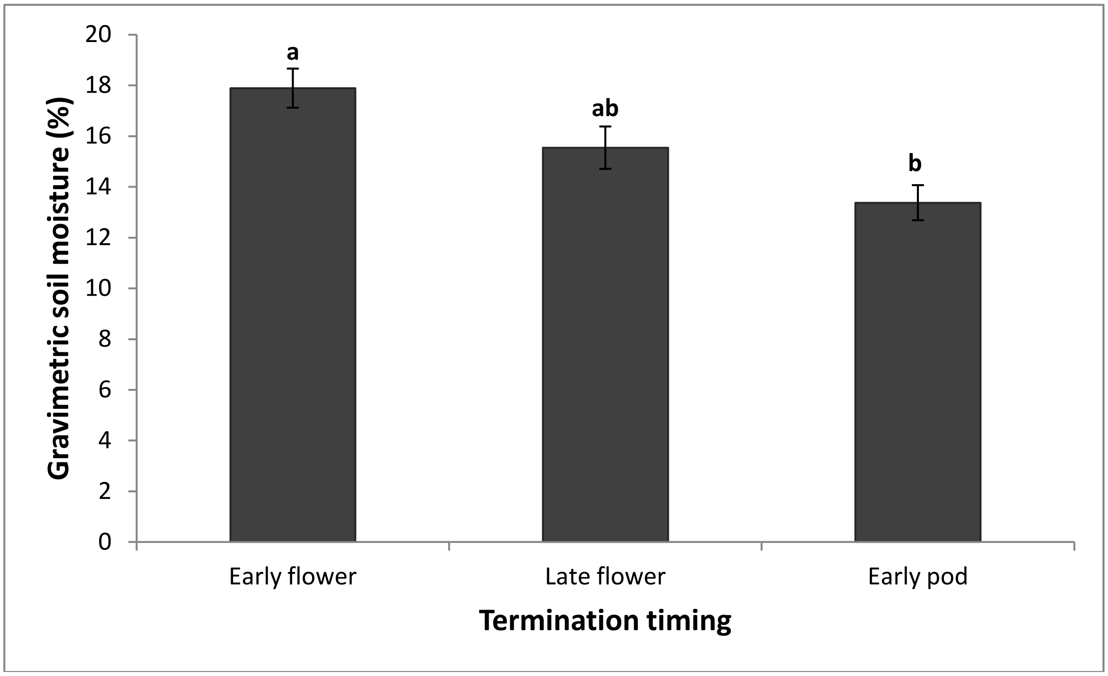

Figure 3.5 Gravimetric soil moisture (30 to 60 cm) as affected by termination timing of field pea green manure at **Kernen** in the fall of 2009. Field capacity was estimated to be 36% (Saxton and Rawls, 2006). Different letters indicate significant differences between termination times at $P<0.05$ according to Tukey's HSD. Bars indicate standard error of means (n=12).

Vonda

At Vonda the tilled plots tended to be highest in soil inorganic N throughout the soil profile, and the rolled plots tended to be lowest (Table 3.14). Soil inorganic N at the surface (0 to 15 cm) was significantly higher for the tilled treatments than the rolled treatments (16.2 and11.0 kg ha^{-1} respectively). Late flower termination tended to increase inorganic N throughout the soil profile; total inorganic N (0 to 45 cm) was significantly higher at late flower than early flower termination (Table 3.14).

Fall 2009 soil moisture showed no consistent trend across the treatments, and neither of the main effects were significant (Table 3.14).

3.3.3.2.1 Microbial biomass

There were no differences in SMB in the 0- to 5-cm depth at either site (Table 3.15). Microbial biomass was measured in late fall of 2009 before cultivation and in the spring of 2010 (Vonda only) after two cultivation events; SMB was not different between treatments at either sampling date. At Kernen, SMB-C&N values were higher than Vonda, but there were no consistent trends within the samples.

3.3.4 Wheat year plant data

In the wheat year only samples from field pea plots were analyzed.

Kernen

Although not significantly higher than the other termination times, field pea termination at early pod tended to result in higher wheat biomass and N uptake throughout the summer and at harvest (Figure 3.6 & 3.7). Termination at early pod resulted in significantly higher seed N concentration and grain protein as compared to late flower termination (Table 3.16). Termination method had no effect on any wheat parameters measured in 2010.

Vonda

Termination method of field pea affected several wheat parameters at Vonda in 2010. Biomass in July and August was significantly greater for mowed treatments than rolled treatments, and July and August N uptake tended to be highest for mowing (Figure 3.8 & 3.9).

Table 3.14 Mean soil inorganic N ($NO_3^- + NH_4^+$) and gravimetric soil moisture at different sample depths as affected by termination method and termination timing of field pea green manure. Samples taken at **Vonda** in the fall of 2009 after green manure termination. ANOVA table showing probability level where effect of source of variation considered significant at $P<0.05$.

Factor	Treatment	Soil inorganic N				Soil moisture		
		Depth (cm)				Depth (cm)		
		0-15	15-30	30-45	0-45	0-15	15-30	30-45
	n=12	--------------- kg N ha^{-1} -------------				---------------- % ----------------		
Termination method	Rolling	**11.0b**†	11.2	6.7	28.9	14.0	11.0	9.1
	Mowing	**14.0ab**	12.0	7.1	33.2	15.5	10.8	10.4
	Tillage	**16.2a**	13.1	9.9	39.2	16.2	10.0	9.4
Termination timing	Early flower	12.7	8.7	5.7	**27.1b**	15.6	10.3	7.9b
	Late flower	16.3	14.6	9.2	**40.1a**	15.9	10.8	9.4ab
	Early pod	12.3	13.1	8.9	**34.2ab**	14.2	10.5	11.6a

Source of variation	------------------------------------Probability *(P)*----------------------------						
Termination method (TM)	**0.0241**	0.7727	0.0949	0.1539	0.2709	0.1822	0.7691
Termination timing (TT)	0.0672	0.0947	**0.0492**	0.0583	0.3757	0.7649	0.0536
TM x TT	0.1604	0.2484	0.1242	0.2134	0.4287	0.0567	0.7686

† Means within a column followed by different letters and bolded are significantly different at $P<0.05$ according to Tukey's HSD; means within a column not followed by letters are not significantly different.

Table 3.15 The effect of termination method and termination timing on mean microbial biomass carbon and nitrogen (SMB-C&N) at 0 to 5 cm in fall of 2009 at Vonda and Kernen, and spring of 2010 at Vonda. Due to high rainfall Kernen was inaccessible for soil sampling in May 2010.

		Vonda				Kernen	
		October 2009		May 2010		October 2009	
Factor	Treatment	SMB-C	SMB-N	SMB-C	SMB-N	SMB-C	SMB-N
		---------------------------- mg kg soil^{-1} -------------------------------					
Termination method	Rolling	648	76	647	93	901	92
	Tillage	693	80	652	91	842	96
Termination timing	Early flower	647	74	649	92	858	87
	Early pod	694	82	651	92	885	101
Source of variation							
Termination method (TM)		0.4752	0.6814	0.8900	0.7770	0.3564	0.8362
Termination timing (TT)		0.4614	0.4158	0.9637	0.8798	0.6662	0.4253
TM x TT		0.6599	0.8549	0.2527	0.3308	0.3907	0.6574

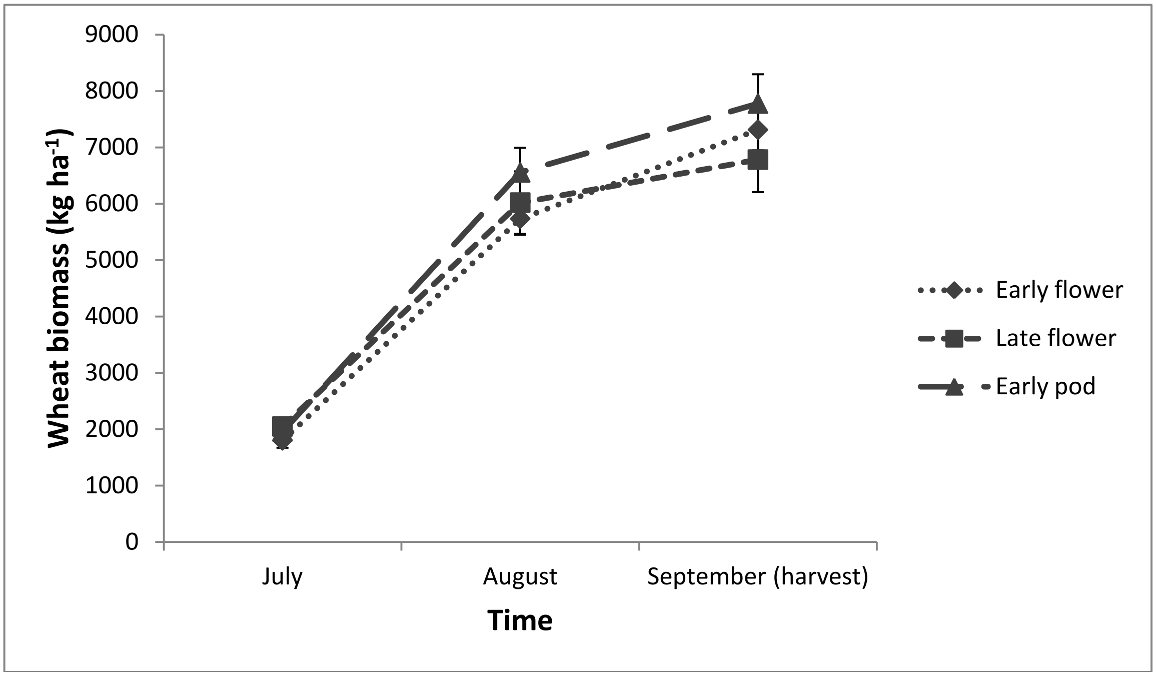

Figure 3.6 Wheat aboveground biomass measured in 2010 as affected by termination timing of field pea green manure in 2009 at **Kernen**. Mean value of three termination methods. Bars indicate standard error of means (*n*=12).

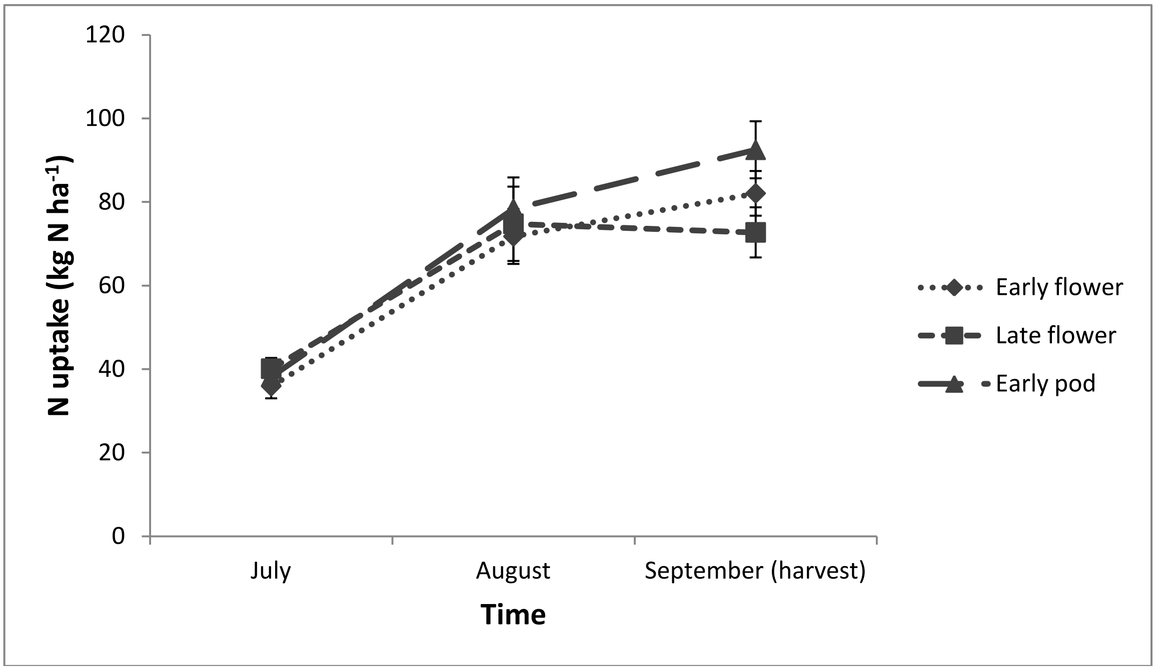

Figure 3.7 Wheat N uptake measured in 2010 as affected by termination timing of field pea green manure in 2009 at **Kernen**. Mean value of three termination methods. Bars indicate standard error of means (*n*=12).

Table 3.16 Mean wheat properties as affected by field pea termination timing. Measurements made on wheat harvested in September 2010 at **Kernen**.

Termination timing	Straw N uptake	Seed N uptake	Wheat yield	Harvest index	Protein content
n=12	--------- kg N ha^{-1}	----------	kg ha^{-1}	%	%
Early flower	31.4[†]	**50.7ab**	1993.3	43.3	**13.0ab**
Late flower	30.0	**42.8b**	1955.0	40.4	**12.5b**
Early pod	36.9	**55.6a**	2155.8	43.0	**13.6a**

Source of variation	-------------------------------	Probability (*P*)	-------------------------------		
Termination method (TM)	0.8582	0.7389	0.9529	0.9630	0.1566
Termination timing (TT)	0.1629	0.0822	0.5750	0.2052	**0.0098**
TM x TT	0.5417	0.8385	0.8660	0.7891	0.8434

† Means within a column followed by different letters and bolded are significantly different at $P<0.05$ according to Tukey's HSD; means within a column not followed by letters are not significantly different.

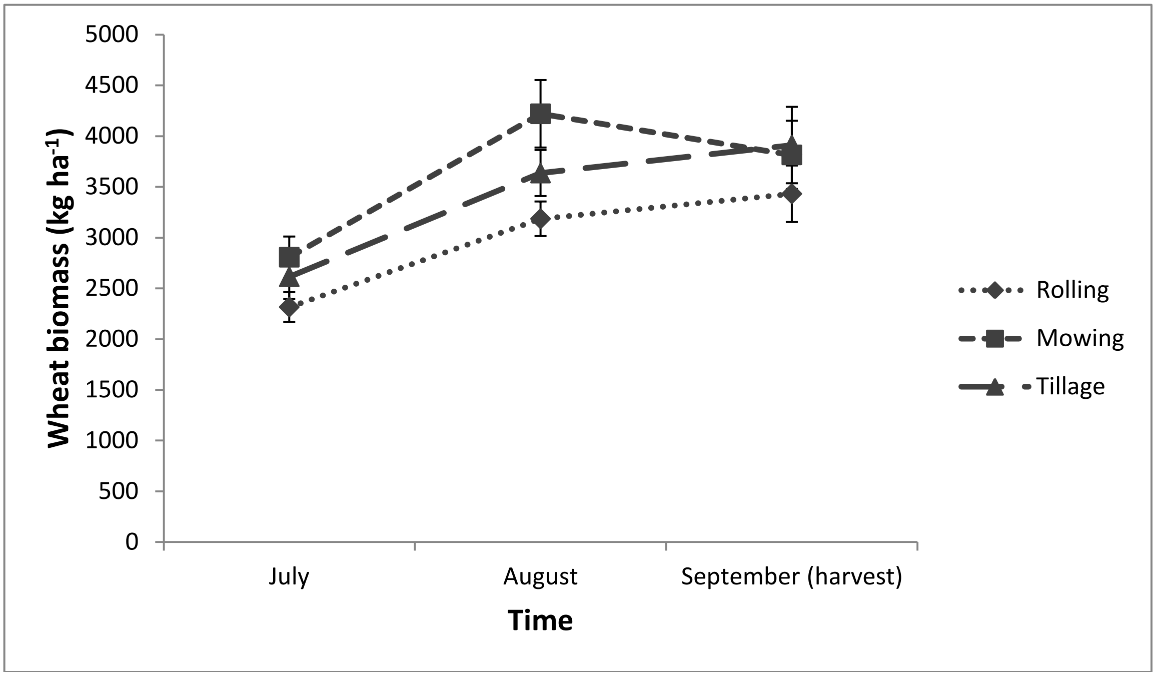

Figure 3.8 Wheat aboveground biomass measured in 2010 as affected by termination method of field pea green manure in 2009 at **Vonda**. Mean value of three termination times. Bars indicate standard error of means (*n*=12).

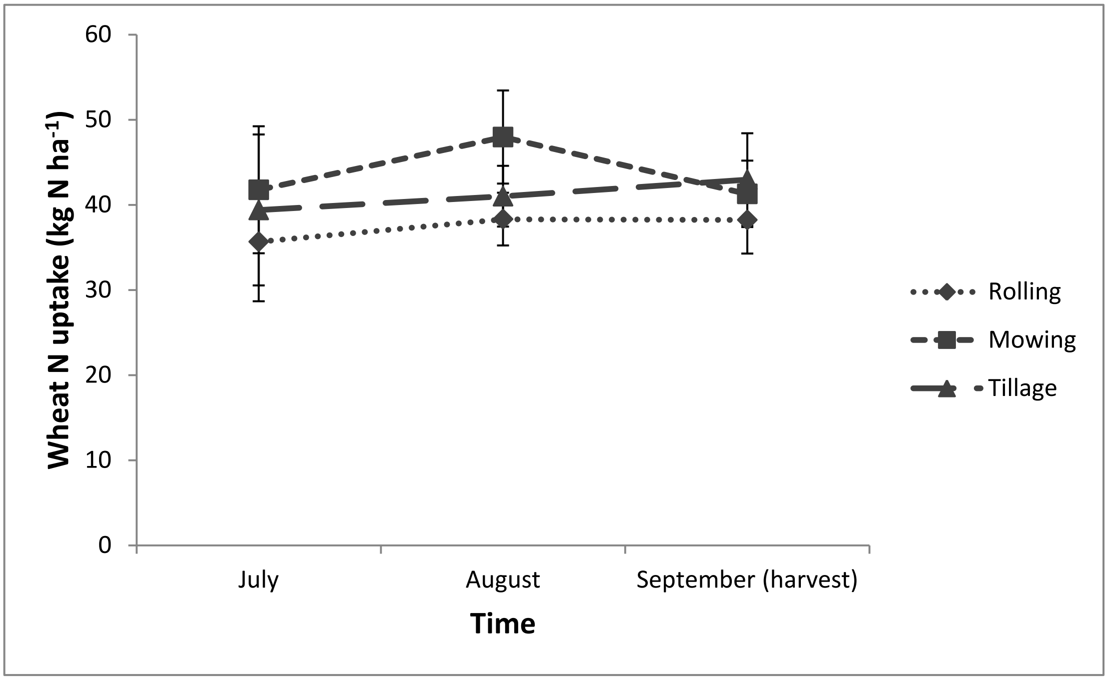

Figure 3.9 Wheat N uptake measured in 2010 as affected by termination method of field pea green manure in 2009 at **Vonda**. Mean value of three termination times. Bars indicate standard error of means (*n*=12).

Wheat biomass and N uptake at harvest (September) was not affected by termination timing or termination method (Figure 3.8 & 3.9). Mowing resulted in the highest wheat yield and protein content (Table 3.17). Termination timing affected yield differently depending on the termination method. Mowing resulted in the highest wheat yield at early flower and early pod, but at late flower mowing lowered wheat yield (Figure 3.10). Late flower termination with tillage resulted in the highest yield, and rolling was unaffected by termination time (Figure 3.10). Grain protein content was highest when field pea was terminated at early pod by tillage, but termination timing did not affect the rolled or mowed plots (data not shown).

3.3.5 Wheat year soil data

Kernen

Soil sampled in 2010 after wheat harvest tended to show lower levels of inorganic N at the 0- to 15- and 30- to 60-cm depths and in the total profile in the tilled field pea treatments, but there were no significant differences among the means (Table 3.18).

There were no differences detected in soil moisture for 2010.

Vonda

The effect of termination timing on soil inorganic N sampled in October 2010 depended on termination method. At 0- to 15-cm (Figure 3.11) and in the total profile (Figure 3.12), early flower termination of field pea with rolling resulted in the highest inorganic N, but at late flower inorganic N was higher with mowing and tillage.

Soil moisture in 2010 was not affected by any treatment.

Table 3.17 Mean wheat properties as affected by field pea termination method. Measurements made on wheat harvested in September 2010 at **Vonda**.

Termination method	Straw N uptake	Seed N uptake	Wheat yield	Harvest index	Protein content
n=12	--------- kg N ha^{-1} ---------		kg ha^{-1}	%	%
Rolling	21.8[†]	16.4	**1510.8b**	28.4	**12.4ab**
Mowing	21.4	19.9	**1840.1a**	30.0	**12.6a**
Tillage	23.3	19.7	**1617.6ab**	32.4	**12.1b**

Source of variation	------------------	------------------ Probability (*P*)	------------------	------------------	------------------
Termination method (TM)	0.7064	**0.0296**	**0.0326**	0.2946	**0.0332**
Termination timing (TT)	0.8697	0.7547	0.5672	0.8266	0.0556
TM x TT	0.2314	0.2355	**0.0498**	0.2116	**0.0003**

† Means within a column followed by different letters and bolded are significantly different at $P<0.05$ according to Tukey's HSD; means within a column not followed by letters are not significantly different.

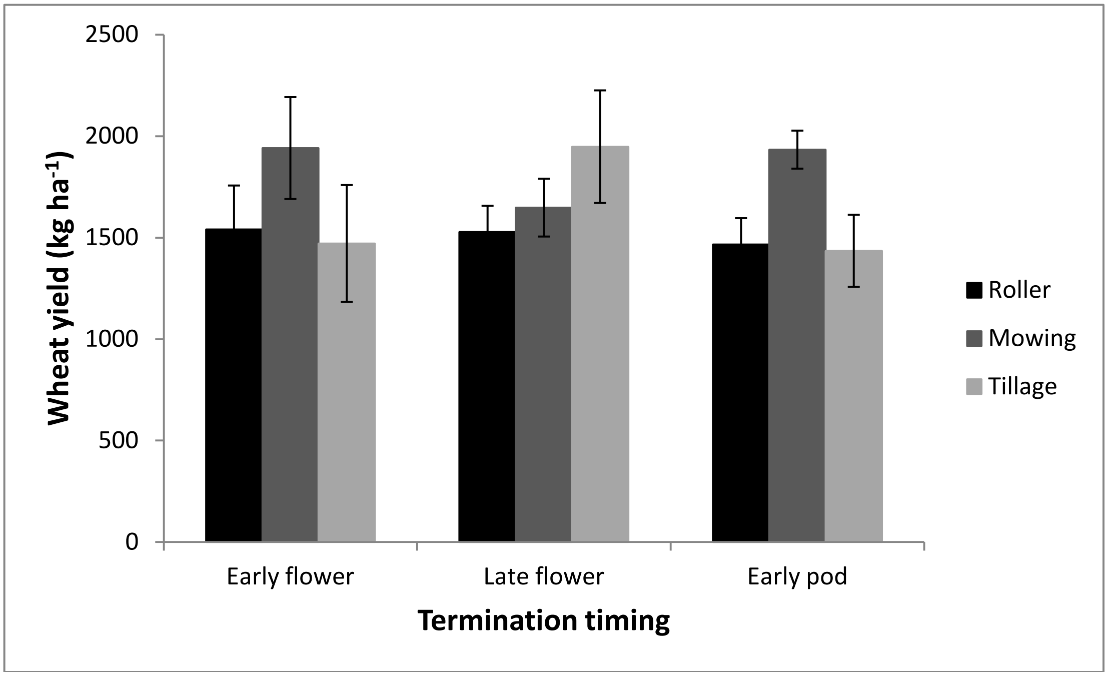

Figure 3.10 Wheat yield as affected by termination timing and method of field pea green manure at **Vonda** in 2010. The interaction between termination timing and method was significant (*P*=0.0498). Mowing resulted in the greatest yield overall (*P*=0.0326). Bars indicate standard error of means (*n*=4).

Table 3.18 Mean soil inorganic N ($NO_3^- + NH_4^+$) and gravimetric soil moisture at different sample depths as affected by termination method of field pea green manure in the previous year. Samples taken at **Kernen** the fall after wheat harvest in 2010. ANOVA table showing probability level where effect of source of variation considered significant at *P*<0.05.

	Soil inorganic N					Soil moisture			
	Depth (cm)					Depth (cm)			
Termination method	0-15	15-30	30-60	60-90	0-90	0-15	15-30	30-60	60-90
n=12	--------------- kg N ha^{-1} --------------					------------------- % --------------------			
Rolling	20.4	5.3	8.7	12.0	46.4	29.71	26.49	25.14	20.39
Mowing	20.3	5.3	9.0	10.5	45.1	32.11	26.87	23.96	19.38
Tillage	14.4	5.9	7.0	12.7	39.9	30.76	25.70	23.41	18.26

Source of variation	---------------Probability *(P)* ---------------								
Termination method (TM)	0.3151	0.5175	0.0457	0.6227	0.3865	0.1195	0.7375	0.6597	0.5283
Termination timing (TT)	0.7163	0.4260	0.2145	0.4707	0.5349	0.3282	0.9731	0.3399	0.5109
TM x TT	0.7680	0.1136	0.4995	0.1372	0.2367	0.9612	0.5221	0.7220	0.3701

Table 3.19 Mean soil inorganic N (NO_3^- + NH_4^+) and gravimetric soil moisture at different sample depths as affected by termination method of field pea green manure in the previous year. Samples taken at **Vonda** the fall after wheat harvest in 2010. ANOVA table showing probability level where effect of source of variation considered significant at P<0.05.

Termination method	Soil inorganic N					Soil moisture†			
	Depth (cm)					Depth (cm)			
	0-15	15-30	30-60	60-90	0-90	0-15	15-30	30-60	60-90
n=12	----------------------- kg N ha^{-1} -----------------------					------------------ % -------------------			
Rolling	11.1	3.7	7.5	8.7	29.6	16.54	11.87	8.74	15.41
Mowing	12.4	4.0	6.4	7.4	30.2	18.85	12.28	11.14	12.18
Tillage	11.6	3.6	6.5	10.0	32.4	17.21	12.81	10.27	10.47

Source of variation	--Probability *(P)* --								
Termination method (TM)	0.7025	0.7469	0.5870	0.4224	0.6336	0.5200	0.2900	0.3837	0.5455
Termination timing (TT)	0.7776	0.8015	0.7486	0.7547	0.8984	0.4486	0.0522	0.9727	0.9496
TM x TT	**0.0349**	0.3235	0.5587	0.1617	**0.0250**	0.6223	0.8112	0.2682	0.8579

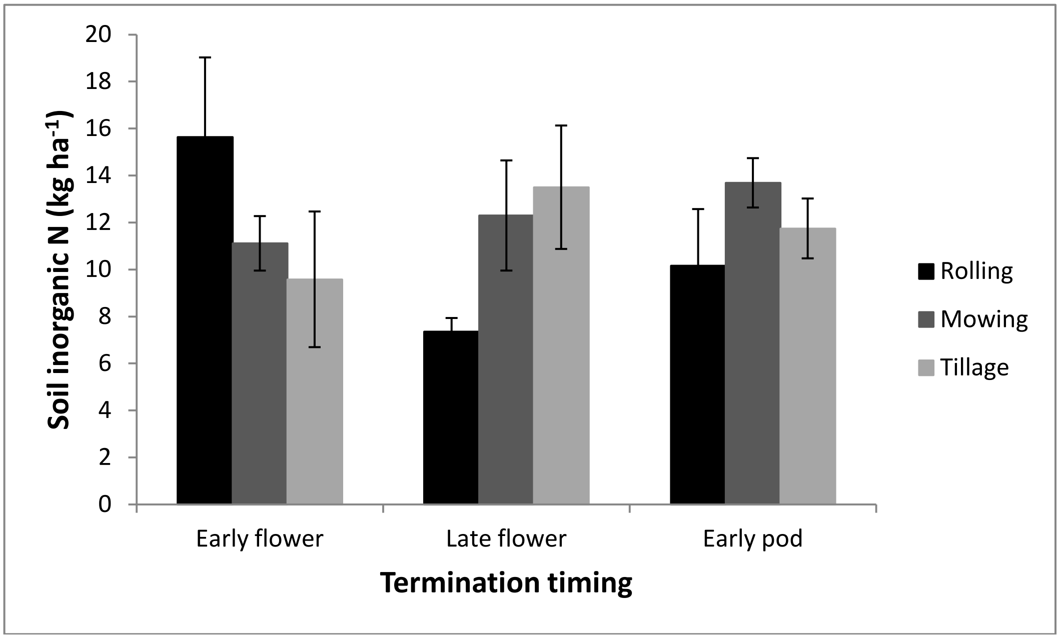

Figure 3.11 Soil inorganic N (NO_3^- + NH_4^+) at 0 to 15 cm measured in October 2010 at **Vonda**. The interaction between termination time and termination method was significant (*P*=0.0348). Bars indicate standard error of means (*n*=4).

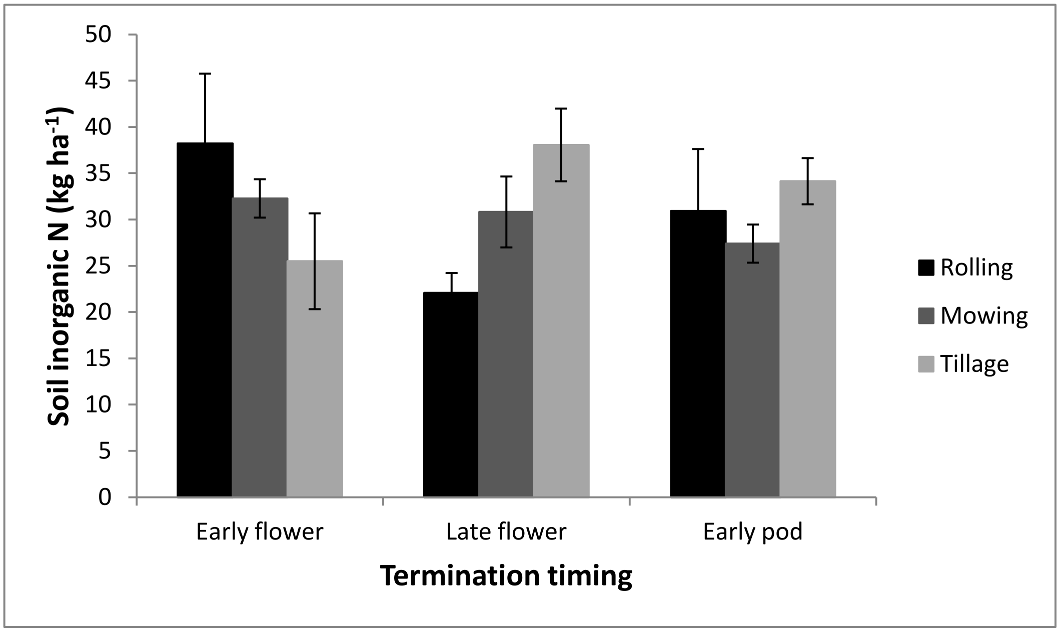

Figure 3.12 Soil inorganic N (NO_3^- + NH_4^+) in the total profile (0 to 90 cm) measured in October 2010 at **Vonda**. The interaction between termination time and termination method was significant (*P*=0.0254). Bars indicate standard error of means (*n*=4).

3.4 Discussion

3.4.1 Comparison of field pea and faba bean

Field pea was more desirable than faba bean as a green manure for an organic system, with over 60% more aboveground biomass and higher nutrient uptake. Previous studies (Turgut et al., 2005; Biederbeck et al., 1998; Townley-Smith et al., 1993) have indicated the relative success of field pea over faba bean and other green manures. Faba bean (cv. Outlook) green manure averaged 56% of the biomass yield of field pea (cv. Trapper) when terminated at full bloom in a green manure-wheat system in Saskatoon, and field pea had the highest N uptake of five green manures (Townley-Smith et al., 1993). The N uptake of field pea was 69 kg N ha^{-1} when used as a green manure preceding corn (*Zea mays*), but only 30 kg N ha^{-1} for faba bean green manure (Turgut et al., 2005). In southern Saskatchewan, a field pea green manure-wheat cropping sequence returned the highest amount of biomass residue, organic C and total N to the soil when compared to chickling vetch (*Lathyrus sativus*), lentil (*Lens culinaris*) and Tangier flatpea (*Lathyrus tingitanus*) green manures and fallow-wheat (Biederbeck et al., 1998). All of these studies were under conventional management, but illustrate the relative success of field pea compared to faba bean and other green manures.

In addition to higher green manure biomass, the field pea plots had lower weed biomass than faba bean plots at termination: at both Kernen and Vonda average weed biomass at termination accounted for ~65% of the total biomass in the faba bean plots and only ~30% in the field pea plots (S.J. Shirtliffe, personal communication, 2009). The 40-10 field pea grows vigorously in both weedy and weed-free conditions, and its branched structure makes it ideal for use in organic systems (Spies et al., 2011). In contrast, faba bean grows tall and slender, which allows light to penetrate and an opportunity for weeds to establish – especially in organic systems. Faba bean is also prone to drought stress and is very sensitive to the level and pattern of water supply (Bryla et al., 2003; Townley-Smith et al., 1993; Bremmer et al., 1988), likely due to the shallow root system (De Costa et al., 1997). In an experiment comparing biomass production of faba bean under different levels of water availability, De Costa et al. (1997) reported that faba bean growth depended on adequate precipitation early in the growing season, and the slightest water shortage caused poor growth and water stress. In the present study, the combination of variable moisture conditions, weed competition, and a high infestation of blister beetles resulted in the poor establishment of faba bean. It is possible that optimal conditions for faba bean establishment may not be found in an organic system in Saskatchewan.

Faba bean remains of interest within the organic community due to reports of high N and P tissue concentration (Townley-Smith et al., 1993; Nurruzzaman et al., 2005), and values of 60-80% Ndfa that result in annual N_2 fixed as high as 125-350 kg N ha^{-1} (Zapata et al., 1987; Carranca et al., 1999; Rochester et al., 1998). At Kernen and Vonda, values ranged from 46-90% Ndfa for faba bean, but N_2 fixed averaged only 20 kg N ha^{-1}. The large discrepancy is due to the low biomass production of faba bean in the present study. Furthermore, the previous studies report N_2 fixed by faba bean at full maturity as a grain legume. Both biomass and N fixation peak at pod fill in legumes (Olson-Rutz et al., 2010), but green manures in Saskatchewan are typically terminated at flower. When grown as grain legumes in years varying from regular precipitation to drought conditions, faba bean consistently fixed more N (up to 91% Ndfa and 55 to 125 kg N ha^{-1} fixed) than field pea (up to 85% Ndfa and 4-107 kg N ha^{-1} respectively) (Carranca et al., 1999). In the present study, average %Ndfa was equivalent for the two green manures and ranged from 65 to 80%, while N_2 fixed was significantly higher for field pea. In contrast, a conventional green manure-wheat rotation in Saskatoon reported equivalent N_2 fixed values of 40 kg N ha^{-1} for both faba bean and field pea (Townley-Smith et al., 1993). The average N_2 fixed by field pea at Kernen and Vonda was 45 kg N ha^{-1}. For both green manure crops there was a marked increase in %Nfda from early flower to late flower, which supports a previous finding that N_2 fixation increases through flowering (Zentner et al., 2004).

In the Townley-Smith et al. (1993) report, faba bean had the highest N content (32 g N kg^{-1}) of five green manures, including field pea (26 to 29 g N kg^{-1}). Faba bean had double the total P content of field pea in an indoor pot study comparing field legumes, and faba bean was concluded to be a suitable P-mobilizing legume (Nuruzzaman et al., 2005). These findings are consistent with results from Kernen: N and P content of faba bean (27 g N kg^{-1} and 3 g P kg^{-1}) were higher than field pea (18 g N kg^{-1} and 2 g P kg^{-1}), and faba bean also had narrower C:N and C:P's than field pea. These nutrient qualities of faba bean are desirable in an organic system, considering that net N and P mineralization are positively correlated with N and P content and negatively correlated with C:N and C:P's (Lupwayi et al., 2006a; Kwabian et al., 1987; Hundal et al., 1987).

However, the high N and P content in faba bean may be due to a concentration effect as a result of stunted growth (Carranca et al., 1999) compared to the dilution of nutrients in the larger pea biomass. A more appropriate indication of a green manure's nutrient contribution to a system is plant N and P uptake because it is based on the total amount of biomass produced and hence returned to the system (kg N or P ha^{-1}). Although N content was higher in faba bean than field pea, N uptake in field pea (166 kg N ha^{-1}) was higher than faba bean (119 kg N ha^{-1}) when terminated at full bloom, which in turn contributed more N to the cropping system (Townley-Smith et al., 1993). Similarly, N and P uptake by field pea at Kernen and Vonda was 50% higher than faba bean, which resulted in higher soil inorganic N and P (0 to 60 cm) measured in the field pea plots the fall after termination.

Significant N mineralization occurs within 3 to 4 weeks after incorporation of legume residues (Drinkwater et al., 2000), suggesting that soil samples taken in October following green manure termination would already show treatment effects. Higher N and P uptake by field pea corresponded with higher average fall inorganic N and P at Kernen, and higher inorganic N at Vonda. Soil inorganic P following green manure termination was unaffected at Vonda, likely due to initial soil P levels of > 60 kg ha^{-1}. Nitrogen uptake by field pea and faba bean was higher at Vonda than Kernen, resulting in narrow C:N's at Vonda. Average %Ndfa was also higher at Vonda than Kernen, accounting for higher N content in the plant tissues. Higher P content in the soil can improve BNF (Olson-Rutz et al., 2010), as demonstrated at Vonda.

The effect of termination method on soil inorganic N measured in the fall of 2009 was different at the two sites, and likely related to C:N. At Kernen, where field pea had a wider C:N than faba bean (23:1 *vs* 15:1), termination by tillage resulted in the lowest soil inorganic N for the field pea treatments (24 kg N ha^{-1}) and termination by rolling the highest (32 kg N ha^{-1}). In contrast, termination by tillage resulted in the highest soil inorganic N in the faba bean treatments (28 kg N ha^{-1}). In a 12-wk incubation study, Enwezor (1976) applied different crop residues to soil samples and determined that net mineralization ceased between a C:N of ~16:1 to 24:1. With incorporation, the C-rich residue of field pea may have immobilized N, while the N-rich faba bean residue mineralized and released N to the soil more quickly. The rolled green manures persisted as intact mulches longer on the soil surface than the tilled treatments, and it may have been too early in the decomposition process to influence soil N by fall of 2009. At Vonda, the average C:N was narrow and equivalent (16:1) for field pea and faba bean, and tillage resulted in the highest soil inorganic N for both crops. These findings suggest that when green manures have a wider C:N, termination by rolling is preferred to tillage because the residues are not incorporated right away and do not immobilize N.

The soil properties measured in 2009 indicate that faba bean behaved more closely to a summerfallow than a green manure crop. Summerfallow is used to store soil moisture and provides mineralized N as tillage breaks up the soil aggregates; however, it results in increased soil degradation (Campbell et al., 1991). In contrast, green manures protect the soil from wind and water erosion and add available-N to the soil through N_2 fixation (Biederbeck et al., 1996). Faba bean was not planned as a summerfallow in this experiment, and therefore cannot be compared as such. The remainder of the results will discuss field pea only.

3.4.2. Termination effects of field pea

Termination timing of field pea affects soil moisture in the semi-arid agricultural region of the Northern Great Plains, which encompasses central Saskatchewan. Typically the earlier field pea is terminated the more soil water is conserved for the subsequent crop in both organic and conventional systems (Zentner et al., 2004; Knight and Shirtliffe, 2005; Miller et al., 2006, 2008, 2011), but there was no clear relationship between termination timing and soil moisture in the present study. A long-term study in Swift Current, SK illustrated the importance of green manure termination timing to subsequent wheat yield: after 6 yr of terminating lentil (*Lens culinaris*) green manure at full bloom (late July to early August), wheat yield equaled that after summerfallow; but when lentil was terminated in early July the wheat yield surpassed that following fallow (Zentner et al., 2004). In the present study soil moisture (0 to 15 cm) decreased with each termination date when measured in July and August of 2009, but no differences were detected in soil moisture at the surface (0 to 15 cm) in the fall of 2009 following termination. Total precipitation in the fall of 2009 was greater than the long-term average (LTA) of the two sites, and especially higher at Kernen. Kernen received 63 and 95 mm of precipitation in September and October 2009 respectively, which is more than double the LTA averages of 31 mm in September and 17 mm in October (Environment Canada). Vonda received 35 mm in September and 63 mm in October; the LTA averages are 43 and 26 mm, respectively (The Weather Network). With average soil moisture only 4% less than FC at Kernen, no treatment differences were detected at the surface, but termination timing affected the deeper soil moisture reserves. Termination of field pea at early flower conserved more soil water at the 30- to 60-cm depth than when terminated 23 d later at early pod. Similarly, in a study conducted in Montana (Miller et al., 2011) terminating spring pea 20 d after first bloom at pod-development depleted soil moisture a further 53 mm throughout the profile (0 to 120 cm).

The adoption of NT in conventional agriculture is known to increase soil water storage, and rolling a green manure in an organic system in Manitoba conserved soil moisture as compared to tillage (Vaisman et al., 2011). At Kernen, soil moisture was highest in the rooting zone (15 to 30 cm) of the rolled plots and lowest in the tilled plots. Similarly, in the spring following sweet clover termination in semi-arid Alberta, soil moisture under mowed plots was higher than plots disced to 10 cm or ploughed to 15 cm (Blackshaw et al., 2010). In that study, it was suggested crop residues left on the surface in the mowed treatments may have improved snow trapping and reduced evapotranspiration. Due to fall tillage in the present study, the snow-trapping advantage of the surface residues did not exist, and there were no soil moisture differences in the spring or fall of 2010.

The study by Vaisman et al. (2011) was the first to use the roller-crimper on the Canadian prairies, and clearly demonstrated the effect of green manure termination method on soil inorganic N and wheat yield. The objective was to compare green manure termination by tillage, rolling, or combinations of the two on N availability and N uptake the following year. Termination methods were repeated four times throughout the summer and fall; there were six treatments ranging from tillage only to rolling only. In the late fall following termination, soil nitrate-N to a 60 cm-depth was higher in the tilled-only system than the rolled-only system, and the following wheat yield was significantly lower in the rolled-only plots. When rolling and tillage were combined, the rolled-twice, tilled-twice treatment had similar soil nitrate at 0 to 30 cm as the tilled-only treatment, but had significantly less nitrate at 30 to 60 cm than the tilled-only treatment (Vaisman et al., 2011). The combination treatment maintained a wheat yield equivalent to the tilled-only treatment while reducing the risk of nitrate leaching; total profile soil nitrate was almost 40% less in the combination treatment. After a 4-yr organic rotation under NT in California, Drinkwater et al. (2000) reported that alternating a year of NT with discing was necessary to attain a profitable maize (*Zea mays*) yield.

At Vonda, fall inorganic N tended to be highest throughout the profile in the tilled plots, but after tillage in the fall and spring, wheat yield in the tilled plots was equivalent to the mowed and rolled treatments. There are several reasons why tillage results in higher inorganic N or increased crop yield. Repeated tillage mineralizes SOM (Drinkwater et al., 2000) as aggregates are broken up and become accessible to microbial attack. Treatment differences in the Vaisman et al. (2011) study were distinct due to the repeated termination events; not only were the residues mineralized but also the native SOM. The surface area of residues and the residue-to-soil contact is increased with tillage, which exposes the material to microbial attack and also increases mineralization (Lupwayi and Burr, 2010). Legume residues with narrow C:N, such as field pea at Vonda (16:1), mineralize N quickly and release significant N in the weeks following incorporation (Drinkwater et al., 2000). Mineralization of field pea tilled at termination likely occurred in the first few months, whereas mineralization of the mowed and rolled residues was stimulated with spring tillage. The aeration provided by spring tillage increases soil temperature, and in turn mineralization. Adding spring tillage to the rolled-only treatment in Manitoba improved early wheat development and wheat N uptake over the season (Vaisman et al., 2011).

Incorporation of residues can result in higher inorganic N by preventing volatile losses associated with surface-placed residues. Losses through ammonia volatilization were not measured in the present study; however, ammonia emissions were higher in the rolled-only plots compared to the tilled-only plots in the two experimental years in Manitoba (Vaisman et al., 2011). Total ammonia emitted from the system was 4 to 12 kg ha^{-1} higher in the rolled-only plots and represented 5 to 8% of the original green manure shoot biomass N. Ammonia loss from decomposing green manure mulches can be significant and diminish their fertility benefit (Janzen and McGinn, 1991), but ammonia volatilization did not account for the large nitrate-N difference between the rolled-only and tilled-only systems (Vaisman et al., 2011).

In contrast, rolling field pea at Kernen resulted in higher inorganic N (0 to 60 cm) in the fall of 2009 than termination by tillage. Reduced inorganic N in the tilled field pea plots at Kernen could be due to N immobilization, increased weed re-growth, or a combination of both. Weed re-growth measured in late fall of 2009 was greatest on the tilled plots (P<0.0001) and was affected differently with termination time. While weed re-growth in the tilled and mowed plots varied with termination time, it remained lowest for rolling regardless of termination date. Tillage can stimulate weed germination and mowing has been found to trigger green manure re-growth (Kornecki et al, 2009). Flail mowing generates small pieces of residue that decompose rapidly due to their close contact with soil microorganisms, and therefore allows more light to reach germinating weeds (Creamer and Dabney, 2002). However, weed biomass measured at wheat harvest the following year was unaffected by the treatments at Kernen and Vonda. Vaisman et al. (2011) also found no differences in the weed biomass in the second year of a green manure-wheat system.

Results from Kernen and Vonda illustrate that field pea green manure can be terminated without incorporation of the residues and maintain the same wheat yield and grain protein content as termination with tillage. At Kernen, termination method did not affect wheat N uptake or wheat yield measurements in 2010. The 2009 differences may have been homogenized by the two cultivation events in late fall of 2009 and spring of 2010, or the 150% increase in precipitation over the LTA received in 2010. Furthermore, the slower N release from residues left on the soil surface is most noticeable 4 to 8 weeks after termination, and after 16 weeks the soil N differences between surface and incorporated residues are undetectable (Varco et al., 1989).

At Vonda, mowing resulted in the highest average wheat N uptake, yield and grain protein content. The faster decomposition rate of mowed residues versus rolled residues could explain the lower wheat yield from rolling as compared to mowing. Although tilling field pea resulted in the highest fall inorganic N at Vonda, some soil N may have been lost over the winter and spring. Leaching of N is possible in semi-arid environments when a legume green manure is incorporated followed by a fallow period (Campbell et al., 1994), especially with high precipitation and a sandy-loam textured soil. In September and October of 2009 Vonda received 30 mm more rain than the LTA, and in May of 2010 almost 100 mm more rain than the LTA. Inorganic N in the total profile (0 to 45 cm) in October 2009 was 39, 33 and 29 kg N ha^{-1} in the tilled, mowed and rolled plots, respectively. Although not a large difference between the tilled and mowed plots, mineralization would be further accelerated with late fall tillage, and without N uptake by plants the N was leached lower in the soil profile. Increased soil moisture in the spring of 2010 increased residue mineralization in the rolled and mowed plots.

The slow-release benefit of surface-applied residues has been documented previously on the prairies (Mohr et al., 1999; Blackshaw et al., 2010). A conventional system comparing termination method of alfalfa (*Medicago sativa*) on subsequent wheat N uptake reported the synchronization of N released from alfalfa and taken up by spring wheat was improved with herbicide-terminated (NT) alfalfa compared to tillage-termination (Mohr et al., 1999). Although plant-available N in the spring following alfalfa termination was higher in the tilled plots than the NT plots, wheat yields under NT were similar or greater than those in the tilled plots. Similarly, the slow release of N from herbicide-terminated sweet clover residue seemed to increase wheat protein as compared to clover terminated by tillage in a conventional sweet clover-wheat system in Lethbridge (Blackshaw et al., 2010). These findings are consistent with those from Vonda where mowed treatments resulted in higher grain protein content than tilled treatments. A pattern also emerged at Vonda: tillage at late flower resulted in the highest soil inorganic N measured in the fall of 2009 and 2010, and the highest wheat yield. Field pea N uptake and N_2 fixation were highest at late flower termination, and likely resulted in increased N availability in the system.

Microbial biomass can be used as an early indicator of long-term changes in soil quality associated with management practices (Sparling, 1997). In the short term, incorporation of crop residues with tillage is expected to increase SMB (Jensen, 1997); however, long-term studies report increased SMB at the soil surface in reduced tillage systems compared to conventional (Berner et al., 2008; Omidi et al., 2008; Lupwayi and Burr, 2010). It was therefore expected that SMB would increase in the present study in the fall of 2009 following termination by tillage, as compared to termination by rolling or mowing. It was also expected the differences would be homogenized by the spring 2010 after two cultivation events. However, SMB results from this experiment indicate the treatments were too short-term to detect any differences due to termination method. Alvarez and Alvarez (2000) also found no difference in total SMB-C (0 to 5 cm) between NT and conventional tillage in the first year of the tillage regime change in a continuous-wheat system. However, active SMB concentration was higher at 0 to 5 cm in the NT treatment and decreased with depth, but was the same at 5 to 15 cm for the tilled treatments (Alvarez and Alvarez, 2000). Perhaps if active SMB had been measured at Kernen and Vonda the effects of termination method would have been detected.

3.5 Conclusion

In summary, green manure management affected some of the measured parameters in the green manure year, but in general the differences did not carry over into the wheat year. Green manure biomass, N and P uptake, and C:N increased with each termination date; while soil moisture and inorganic N measured at termination decreased with each termination date. However, termination timing exerted little effect on soil properties and crop uptake after the summer of 2009. Considering the effect of termination timing on crop yield is related to soil moisture, it is possible the wet conditions of 2009 and 2010 masked the effect. Termination method of green manures influenced soil inorganic N in the fall following termination, and crop N uptake the following year at Vonda. Field pea and faba bean responded differently at the two sites, mainly due to inherent soil differences at Kernen and Vonda that resulted in different C:N's. Field pea proved to be a more successful green manure for use in an organic system than faba bean. Field pea can be terminated without incorporation (rolling and mowing at Kernen, mowing at Vonda) in an organic system and maintain the same wheat yield as termination by tillage. Tillage was employed in the green manure-wheat cropping sequence in the late fall and early spring on all plots, but did not result in negative effects on short-term SMB, which is considered an indicator of soil quality. Reduced tillage in a field pea-wheat system is feasible and will likely result in long-term gains that were not detected in this short-term study. According to other research, reduced tillage results in higher SOM, increased water infiltration, increased weed suppression, and reduced energy costs.

4. ALTERNATIVE TERMINATION METHODS FOR A LEGUME/CEREAL GREEN MANURE INTERCROP ON THE CANADIAN PRAIRIES

4.1 Introduction

Organic producers on the Canadian prairies rely on crop rotation, organic inputs and mechanical practices to manage short- and long-term soil fertility, and to control weeds. Green manures are used to replace the nutrients removed from a system during harvest, and the focus has been on maximizing nutrient contribution to the following crop. Legume green manures fix atmospheric N and generally have narrow C:N (<20:1), which results in rapid N release into a system and increased short-term available N (Watson et al., 2002; Fageria, 2007). Incorporating green manures with tillage accelerates N mineralization by increasing the residue to soil contact and soil aeration (Lupwayi and Burr, 2010). While incorporation of legumes results in rapid N mineralization (Drinkwater et al., 2000), tillage also decreases soil organic matter (SOM) and degrades soil quality (Lal, 2007). Careful selection of green manure crops and termination management can release nutrients in synchrony with crop uptake (Handayato et al., 1997), suppress weeds (Morse and Creamer, 2006), increase SOM (Gliessman, 2007), and insulate the soil to prevent moisture loss (Olson-Rutz et al., 2010).

Considering the negative effects of tillage, efforts to reduce tillage in organic agriculture are growing. However, maintaining weed control and sufficient nutrient cycling without tillage is challenging. Current research has focused on replacing tillage for green manure termination with alternative low-disturbance methods, such as rolling or mowing, and optimizing mulch-based weed control. The roller-crimper terminates green manures by rolling over the crop and crimping the stems, thereby killing the plant tissue and leaving a mulch anchored to the ground. Mulches with sufficient biomass can prevent weed germination (Teasdale and Mohler, 1993) and reduce soil evapotranspiration by providing complete soil cover (Ashford and Reeves, 2003; Olson-Rutz et al., 2010). Rolling creates longer-lasting mulches than mowing; mowing generates small pieces of residue that decompose rapidly (Creamer and Dabney, 2002). To attain moderate weed control, it is generally recommended to produce a cover crop biomass of 4000 to 8000 kg ha^{-1}, and >8000 kg ha^{-1} for high weed suppression (Morse and Creamer, 2006). Average aboveground biomass of field pea (*Pisum sativum*) green manure was approximately

2500 kg ha^{-1} in an organic system in Saskatchewan (Chapter 3), while shoot biomass of a field pea/oat (*Avena sativa*) intercrop was 5800 kg ha^{-1} under organic management in Manitoba (Vaisman et al., 2011). Therefore, a legume/cereal intercrop may result in a more effective green manure mulch.

Including a cereal in a green manure intercrop increases mulch biomass and facilitates termination by rolling, but also affects nutrient release to the cropping system. The rate and pattern of N release from residues is partially a function of residue quality (C:N) and termination method (Lupwayi et al., 2006). Green manures with wider C:N's, such as legume/cereal intercrops, decompose more slowly and can temporarily immobilize N (Watson et al., 2002). However, over the long term green manures with wider C:N's build SOM and replenish the organic N pool (Gliessman, 2007). In California, a faba bean (*Vicia faba*)/barley (*Hordeum vulgare*) cover crop produced twice the biomass of a faba bean-only cover crop, and increased SOM by 8.8% after 3 yr (Gliessman, 1987). In contrast, SOM decreased slightly after 3 yr in the faba bean-only cover crop treatment because the narrower C:N caused rapid mineralization. Although causing temporary unavailability, immobilization of soil N by the microbial biomass can conserve soil N resources (Jensen, 1997).

Leaving green manure residues on the soil surface as opposed to incorporation also slows residue decomposition and mineralization, leading to a decrease in available N (Peigné et al., 2007). A study comparing field pea/oat green manure termination by rolling and tillage in Manitoba reported more NO_3-N in the tilled plots at time of subsequent wheat (*Triticum aestivum*) seeding than in the rolled plots (Vaisman et al., 2011). Combining green manure rolling with one tillage event still resulted in lower soil NO_3-N the following spring and lower initial wheat N uptake as compared to the tilled-only treatment (Vaisman et al., 2011). As tillage events were increased, available soil N, wheat uptake and yield increased.

There are several biological and chemical indices used to estimate N mineralization from crop residues and SOM (Griffin, 2008). The effect of tillage on mineralizable N (N_{min}) has been estimated with incubation methods (Miller et al., 2008; Sharifi et al., 2008). The effects of tillage on N_{min} are variable throughout the literature, but N_{min} is considered a sensitive indicator of management-induced changes in Saskatchewan (Carter and Rennie, 1982; Biederbeck et al., 1998). A study conducted on four conventional agriculture sites across Canada compared the long-term effect of no-tillage (NT) and conventional tillage on N_{min} at the 0- to 15-cm depth using a long-term aerobic incubation (Sharifi et al., 2008). A trend towards increased N_{min} under NT management was reported, which is similar to previous studies in Saskatchewan (Soon et al., 2001; Liang et al., 2004); however, the effect tended to vary with soil texture and class (Liang et al., 2004).

Information is lacking on N release from intercropped green manures used as mulches in low-till organic agriculture on the Canadian prairies. Therefore, the objectives of the present study were to determine the effect of field pea/barley termination method on: i) soil NO_3-N the spring following termination; and ii) 4 wk N_{min}, by conducting a short-term aerobic incubation.

4.2 Materials and Methods

4.2.1 Site description

The field experiments were conducted in 2010 and 2011 at the Lethbridge Research Centre (49°38’ N, 112°47’ W) in Lethbridge, AB, and the Kernen Crop Research Farm (52°9’ N, 106°33’ W) near Saskatoon, SK. These sites represent two distinct agro-climatic zones of the Canadian Prairies: semi-arid (AB); and dry sub-humid (SK). The Lethbridge soil is an Orthic Dark Brown Chernozem with a sandy clay loam texture and a pH of 7.8. The Kernen soil is a Dark Brown Chernozem with a clay loam texture and a pH of 6.7. Wet conditions during the growing season of 2010 meant the two sites had very different seeding and management schedules. Growing season precipitation at Kernen was 153% higher in 2010 and 46% higher in 2011 than the long-term average (LTA) (Table 4.1). At Lethbridge, growing season precipitation was 57% higher in 2010 and 26% higher in 2011 than the LTA. Growing season air temperature was within 1˚C of the LTA at both sites in 2010 and 2011 (Table 4.1).

The Kernen site was managed organically for over 10 yr and seeded on land previously cropped to oat. The Lethbridge site had not been managed organically prior to the experiment, and was seeded into an oat cover crop stubble.

4.2.2 Experimental design

In year 1 (2010) of the experiment a green manure intercrop was grown and terminated with different methods, and in Year 2 (2011) spring wheat was sown on all of the plots as a ‘test’

Table 4.1 Mean monthly and crop year temperature, and total monthly and crop year precipitation during the 2010 and 2011 growing seasons at Kernen and Lethbridge (Agriculture and Agri-Food Canada). The 30-yr long-term averages (LTA) are included.

Research Site	Sept. –Apr.[†]	May	June	July	Aug.	Growing season	Crop year[‡]
Air Temperature (°C)							
Kernen 2010	-1.8	10.0	16.0	17.8	16.4	15.1	4.8
Kernen 2011	-4.0	11.5	16.0	18.7	17.6	16.0	1.5
LTA[§]	-4.1	11.8	16.0	18.3	17.6	15.9	2.5
Lethbridge 2010	2.3	8.7	15.1	18.0	17.0	14.7	6.4
Lethbridge 2011	-0.3	10.3	14.7	18.3	18.9	15.6	5.0
LTA[¶]	1.6	11.5	15.4	18.4	17.9	15.8	6.4
Precipitation (mm)							
Kernen 2010	M[#]	143.0	184.0	113.0	58.0	498.0	M
Kernen 2011	M	25.6	119.4	96.3	36.8	287.1	M
LTA	151.5	43.6	60.5	57.3	35.4	196.8	348.3
Lethbridge 2010	250.2	121.2	109.8	59.4	56.4	346.8	597.0
Lethbridge 2011	277.4	98.0	85.4	54.4	39.9	277.7	555.1
LTA	178.2	54.5	84.5	40.8	40.5	220.3	398.5

† September of the previous calendar year until April of the seeding year.

‡ Crop year is from September of the previous year until the end of August.

§ Long-term average from 1971-2001 for Saskatoon (52°09’ N, 106°36’ W) (Environment Canada).

¶ Long-term average from 1981-2010 for Lethbridge (49°38′ N, 112°47′ W) (Agriculture and Agri-Food Canada).

M: missing data for some sample periods.

crop. The experiment compared four green manure termination treatments: 1) standard soil tillage (tandem disc); 2) roller-crimper; 3) roller-crimper followed by late-fall tillage (or cultivation); or 4) flail mower. A summerfallow control plot was included at Lethbridge. The experimental design was a randomized complete block design (RCBD) with 4 replicates. Individual plot size was 4 by 10 m. The present study focused on soil and plant measurements in the green manure year and spring soil sampling in the wheat year.

A green manure intercrop of field pea (cv. 40-10) and barley (cv. CDC Cowboy) was seeded 7 June 2010 at Kernen and 1 July 2010 at Lethbridge with a Fabro double-disc zero till drill. Seeding density was 80 seeds m^{-2} for field pea and 42 seeds m^{-2} for barley. Pea and barley were seeded in the same operation to a depth of 6.5 cm, and the row spacing was 11.5 cm. Field pea was inoculated with Nodulator XL (Becker Underwood, USA) at Kernen, and inoculated at Lethbridge with Cell-Tech liquid inoculant (Novozymes, CAN) at a rate of 3 mL kg $seed^{-1}$.

On 20 July 2010 at Kernen the pea/barley green manure was terminated at early flower of the barley crop with two passes of a tandem disc, roller-crimper, or flail mower. The termination treatments were repeated at Kernen on 19 August, and at this time Treatment 3 was tilled with a tandem disc. The initial termination at Lethbridge was on 3 September 2010, 10 d post-heading of barley. Initial termination was accomplished with one pass of an offset disc and two passes of the roller and mower for each respective treatment. Termination of the rolled plots was repeated on 12 October, and termination of the mowed plots was repeated on 21 October. Finally, on 27 October Treatment 3 was cultivated with one pass at Lethbridge. The summerfallow control at Lethbridge was cultivated on 29 July and 3 September 2010.

Spring wheat (cv. AC-Superb) was seeded on all plots at 400 seeds m^{-2} on 13 and 18 May 2011 at Kernen and Lethbridge respectively, using a Fabro double-disc zero till drill. Wheat was seeded at a row spacing of 20 cm, to a depth of 5.5 cm.

4.2.3 Soil sampling and analysis

Soil samples were taken approximately one week before green manure termination using a backsaver probe (3.5-cm diameter). Eight 0- to 15- and 15- to 30-cm samples were taken randomly within each replicate and composited by depth. Sampling occurred on 20 July 2010 at Kernen and 24 August 2010 at Lethbridge. Samples were stored field moist at 4°C until analyses were performed.

On 12 May 2011, soil was sampled from the treatments at Kernen before spring wheat was seeded. Dutch augers (4-cm diam.) were used to take 0- to 15-, 15- to 30-, 30- to 60-, and 60- to 75-cm samples from all treatment plots. The earliest it was possible to sample in 2011 at Lethbridge was 30 June due to the wet soil conditions. A punch truck was used to take one core (4-cm diam.) from each plot. The core was divided into 0- to 15-, 15- to 30-, 30- to 60-, and 60- to 90-cm increments. All samples were stored field moist at 4°C until analysis.

Gravimetric soil moisture was determined on all soil samples by weighing 5 to 10 g moist soil, drying it for 48 hours at 110°C, and then re-weighing. Gravimetric soil moisture was calculated according to Eq. [4.1]:

$$\text{Gravimetric soil moisture (\%)} = \frac{\text{wet soil} - \text{dry soil}}{\text{dry soil}} \times 100 \qquad [4.1]$$

Soil NO_3-N and NH_4-N of all soil samples taken were extracted with 2.0 *M* KCl (Maynard et al., 2008): 5 g of field moist soil was shaken with 50 mL 2.0 *M* KCl for 1 hr at 142 rpm on a rotary shaker, then filtered through VWR 454 filter paper (VWR International). All extracts were kept at 4°C until the concentrations were measured on a SmartChem (Westco Scientific Instruments, Inc, Brookfield, CT). Soil NO_3-N and NH_4-N of the initial samples in 2010 were summed and are referred to as “Inorganic N”. Ammonium-N was below the detection limit in the 2011 samples, and therefore soil NO_3-N is reported as “Inorganic N”.

4.2.3.1 N mineralization

The 0- to 15-cm soil samples taken in 2011 at Kernen and Lethbridge were used to measure 4 wk mineralized N (N_{min}) of the different termination treatments. A short-term aerobic incubation was conducted using the method of Scott et al. (1998) and Parfitt et al. (2005). First, a bulk sample from all of the treatments was used to estimate field capacity (FC). Soil was placed in a 5- x 15-cm plastic column that was closed at one end with cheesecloth, and placed upright in a bucket of sand. The soil was saturated with water and the open end of the column covered with Parafilm®. After 48 h three 10-g samples were taken from within the column and gravimetric soil moisture of the three samples was determined according to Eq. [4.2]. An average of the three samples was calculated.

The moist soil samples were sieved through a 4-mm sieve and two, 5-g dry weight equivalent of each sample were weighed into dram vials. Each was adjusted to 80% field capacity by adding water to the vial. The first set of samples was extracted with 2.0 *M* KCl immediately, and the second set was prepared for incubation. The dram vials were covered with Parafilm®, placed in a closed polypropylene container (Tupperware) filled partly with water, and incubated at 25°C for 28 d. Four holes were made in each Parafilm® cover and the Tupperware was opened every 3 d to reintroduce oxygen into the system to prevent development of anaerobic conditions. After 28 d, the samples were extracted with 2.0 *M* KCl and analyzed as described above. Four wk N_{min} was calculated by subtracting initial soil inorganic N from inorganic N determined at the end of the incubation.

4.2.4 Plant sampling and analysis

At Kernen, green manure aboveground biomass was sampled by cutting all of the plant material at ground level from two, 2-m rows per plot on the day of termination. At Lethbridge, aboveground biomass was sampled in the same manner from two, 0.5-m rows per plot the day prior to termination. Weeds were separated from the crop plant samples at Kernen, but not at Lethbridge. Weed content was less than 10% of the green manure biomass samples taken at Lethbridge. The green manure plant samples were dried for 10 d at 50°C.

Oven-dried green manure samples were ground to 2 mm with a Wiley Mill (Thomas Scientific, Swedesboro, NJ). Total C was analyzed by combustion at 1100°C using a LECO C632 Carbon determinator (LECO Corporation, St. Joseph, MI). Total N concentration (µg g^{-1}) of the green manure samples was determined by acid digestion (Thomas et al., 1967) and analyzed on the SmartChem (Westco Scientific Instruments, Inc, Brookfield, CT). Green manure N uptake (kg ha^{-1}) was calculated according to Eq. [4.2]:

$$\text{N uptake (kg ha}^{-1}\text{)} = \frac{\text{[dry weight (g m}^{-2}\text{)] x [N concentration (}\mu\text{g g}^{-1}\text{)]}}{10^5} \qquad [4.2]$$

4.2.5 Statistical analysis

Data was analyzed as a 1-way randomized complete block design using ANOVA in CoStat (CoHort Software, Monterey, CA). Termination method was considered significant at *P*

< 0.05. Means within treatments were compared using Tukey's HSD at the 5% level of significance.

4.3 Results

4.3.1 Soil data

At green manure termination in July, soil moisture ranged from 21 to 24% at Kernen. Field capacity (33 kPa) at Kernen was estimated to be 36%, based on a clay loam texture and 2.5% organic matter (Saxton and Rawls, 2006). Mean inorganic N at termination was low at Kernen and none of the samples exceeded 20 kg ha^{-1} (Table 4.2). At Lethbridge, mean soil moisture and inorganic N were higher for the summerfallow control plots than the treatment plots at termination (Table 4.2). Soil inorganic N ranged from 48 to 100 kg ha^{-1} at Lethbridge. The estimated FC (33 kPa) at Lethbridge, based on a sandy clay loam texture and 2.5% organic matter, was 27% (Saxton and Rawls, 2006)

Soil moisture measured in May of 2011 was unaffected by green manure termination method at Kernen (Table 4.3). Soil inorganic N was highest for the tilled treatments at all sample depths measured in the spring of 2011 at Kernen (Table 4.3). The rolled green manure treatments consistently had lower soil NO_3-N than the tilled treatments at each sample depth. Soil inorganic N measured in the rolled + fall tillage and mowed treatment was not significantly lower than the tilled treatments at 0 to 15 cm.

At Lethbridge, mean soil moisture measured in May 2011 was unaffected by green manure termination method and ranged from 17 to 25% (Table 4.4). Soil inorganic N measured in May tended to be highest for the control and tilled treatments throughout the soil profile (Table 4.4). Inorganic N in the summerfallow control plots was significantly higher than all other treatments at 15 to 30 cm, and the tilled treatment was significantly higher than the rolled treatment.

Table 4.2 Mean gravimetric soil moisture and soil inorganic N (NO_3^- and NH_4^+) measured at green manure termination. Soil at Kernen sampled the day of termination (20 July 2010), and at Lethbridge sampled 10 d before termination (24 August 2010).

		Soil moisture		Soil inorganic N	
		Depth (cm)		Depth (cm)	
Site	Plot	0-15	15-30	0-15	15-30
		------------ % -----------		------- kg N ha^{-1} -------	
Kernen	Treatment (n=4)	24.0[†]	21.4	15.8	6.2
Lethbridge	Treatment (n=8)	**19.3b**	**18.9b**	**48.1b**	47.9
	Control[‡] (n=4)	**21.8a**	**22.0a**	**100.3a**	62.4

† Means within the same column of each site followed by different letters and bolded are significantly different at $P<0.05$ according to Tukey-Kramer; means within the same column of each site not followed by letters are not different.

‡ Lethbridge summerfallow control was cultivated 29 July 2011.

Table 4.3 Mean gravimetric soil moisture and soil inorganic N (NO_3^-)(n=4) at different sample depths as affected by green manure termination method. Soil samples in May of 2011 following green manure termination in 2010 at **Kernen**.

	Soil moisture				Soil inorganic N				
	Depth (cm)				Depth (cm)				
Termination method	0-15	15-30	30-60	60-90	0-15	15-30	30-60	60-90	0-90
	%				kg N ha^{-1}				
Tillage	26.1[†]	30.5	24.0	22.1	**37.9a**	**33.2a**	**31.5a**	**19.7a**	**122.3a**
Rolling	27.1	35.1	26.5	22.6	**22.0b**	**11.7b**	**12.5b**	**5.4b**	**51.7b**
Rolling + tillage	29.9	30.2	36.6	20.8	**25.5ab**	**9.7b**	**11.5b**	**2.7b**	**50.0b**
Mowing	28.3	41.7	40.3	20.5	**26.5ab**	**13.0b**	**19.2ab**	**8.0b**	**66.8b**

† Means within a column followed by different letters and bolded are significantly different at $P<0.05$ according to Tukey-Kramer; means within a column not followed by letters are not significantly different.

Table 4.4 Mean gravimetric soil moisture and soil inorganic N (NO_3^-) (n=4) at different sample depths as affected by green manure termination method. Soil samples taken in June of 2010 following green manure termination in 2010 at **Lethbridge**.

Termination method	Soil moisture				Soil inorganic N				
	Depth (cm)				Depth (cm)				
	0-15	15-30	30-60	60-90	0-15	15-30	30-60	60-90	0-90
	%				kg N ha^{-1}				
Tillage	17.0†	18.0	23.2	24.6	**27.9a**	**35.9b**	161.4	342.2	567.5
Rolling	19.6	20.1	25.3	22.7	**15.8b**	**17.2c**	229.3	259.2	521.5
Rolling + tillage	18.1	18.9	20.1	22.1	**18.1ab**	**22.1bc**	177.9	248.2	466.3
Mowing	18.1	20.1	22.0	23.7	**15.4b**	**20.0bc**	185.9	281.1	497.1
Control	16.9	20.7	24.0	23.2	**30.7a**	**55.2a**	165.4	305.9	557.1

† Means within a column followed by different letters and bolded are significantly different at $P<0.05$ according to Tukey-Kramer; means within a column not followed by letters are not significantly different.

4.3.1.1 N mineralization

Initial soil inorganic N in the May 2011 samples (0 to 15 cm) determined before the aerobic incubation began was highest under the tilled green manure treatment (37.6 kg N ha^{-1}) and lowest under the rolled treatment (23.5 kg N ha^{-1}) at Kernen (Table 4.5). Soil inorganic N measured after the 28 d incubation was higher under the tilled treatment than all other treatments at Kernen. Four wk mineralized N (N_{min}) calculated after the incubation period was highest for the tilled treatment (27.2 kg N ha^{-1}) and lowest for the rolled + fall tillage treatment (7.2 kg N ha^{-1}) (Table 4.5). The rolled and mowed treatments were similar, and not significantly different from the other treatments.

At Lethbridge, there were no statistical differences in the initial soil inorganic N of the May 2011 samples (0 to 15 cm), but the summerfallow control and tilled treatments tended to be highest (Table 4.6). Mean inorganic N measured after the 28 d incubation also was unaffected by the termination treatments and values ranged from 23 to 30 kg N ha^{-1}. Four wk N_{min} was lowest for the tilled treatment (7.6 kg N ha^{-1}) and highest for the rolled treatment (18.1 kg N ha^{-1}) at Lethbridge.

4.3.2 Plant data

At Kernen, mean green manure biomass (field pea and barley combined) at initial termination was 1319 kg ha^{-1} (Figure 4.1) with a C:N ratio of 20:1 (Table 4.7). Mean N uptake by the green manure was 29.8 kg N ha^{-1}. Initial termination by rolling did not successfully kill the green manure (S. Campbell, personal communication, 2010), and the crop regrew within 10 d after rolling (Figure 4.2). The second termination event in August improved the crop kill, and the mulch was laid closer to the soil surface (Figure 4.2). Tillage and mowing successfully terminated the green manure, but increased soil exposure. The rolled treatment had the thickest mulch based on observation into the fall (Figure 4.3), and tilling the rolled mulch greatly increased soil exposure (Figure 4.4).

At Lethbridge, mean green manure biomass was 4955 kg ha^{-1} (Figure 4.1) and included field pea, barley and weeds. Weed content was less than 10% of the entire green manure sample. The green manure C:N at termination was 14:1 at Lethbridge, and the mean N uptake was 155.6 kg N ha^{-1} (Table 4.7). Photographs were not taken at Lethbridge throughout the green manure season.

Table 4.5 Mean soil inorganic N (NO_3^-) (0 to 15 cm) measured initially, after a 28 d aerobic incubation, and calculated 4 wk mineralized N (N_{min}) as affected by green manure termination method. Soil sampled in May 2011 following green manure termination in 2011 at **Kernen.**

Termination method	Initial soil N	28 d soil N	N_{min}
	------------------------ kg N ha^{-1}	----------------------	
Tillage	**37.6a**[†]	**64.8a**	**27.2a**
Rolling	**23.5b**	**36.9b**	**13.4ab**
Rolling + tillage	**27.2ab**	**34.4b**	**7.2b**
Mowing	**26.7ab**	**43.8b**	**15.9ab**

† Means within a column followed by different letters and bolded are significantly different at $P<0.05$ according to Tukey-Kramer.

Table 4.6 Mean soil inorganic N N (NO_3^-) (0 to 15 cm) measured initially, after 28 d aerobic incubation, and calculated 4 wk mineralized N (N_{min}) as affected by green manure termination method. Soil sampled in June 2011 following green manure termination in 2011 at **Lethbridge.**

Termination method	Initial soil N	28 d soil N	N_{min}
	----------------------- kg N ha^{-1}	----------------------	
Tillage	21.7[†]	29.4	**7.6b**
Rolling	12.0	30.1	**18.1a**
Rolling + tillage	13.0	28.9	**15.9ab**
Mowing	11.5	22.9	**11.4ab**
Control	22.0	29.9	**7.9ab**

† Means within a column followed by different letters and bolded are significantly different at $P<0.05$ according to Tukey-Kramer; means within a column not followed by letters are not different.

Figure 4.1 Field pea/barley green manure at Kernen (left) on the day of termination, and at Lethbridge (right) 10 d before termination. Green manure was terminated at early flower of barley at Kernen (inset) and produced 1319 kg ha^{-1} biomass. Green manure was terminated 10 d post-heading of barley at Lethbridge (inset) and produced 4955 kg ha^{-1} biomass.

Table 4.7 Mean green manure (field pea and barley) biomass, C to N ratio, N concentration, and N uptake measured at termination at Kernen and Lethbridge in 2010 (*n*=8).

Site	Biomass[†]	C:N	N conc.	N uptake
	kg ha^{-1}		g kg^{-1}	kg N ha^{-1}
Kernen	1319	20	22.6	29.8
Lethbridge	4955[‡]	14	31.4	155.6

† Biomass data collected by Dr. Shirtliffe's research group at Kernen and Dr. Blackshaw's research group at Lethbridge.

‡ Biomass of pea, barley and weeds. Weed content was less than 10%.

Figure 4.2 Field pea/barley green manure 10 d after first termination event in July (left) and immediately after the second termination event in August (right) at **Kernen.**

Figure 4.3 Field pea/barley mulch in a rolled plot (left) and a mowed plot (right) after two termination events at **Kernen**. Photographs taken on 7 October 2010, 6 wk after final termination event.

Figure 4.4 Field pea/barley mulch after two termination events at **Kernen.** Photographs taken on 7 October 2010, 6 wk after final termination event.

4.4 Discussion

Soil inorganic N measured at green manure termination was substantially lower at Kernen (15.8 kg N ha^{-1}) than Lethbridge (48 to 100 kg N ha^{-1}) at the 0- to 15-cm depth. The discrepancy was likely because the Lethbridge site was in its first year of organic management, and received chemical fertilizers in previous years. A higher level of inorganic N in the control plots than the treatment plots at Lethbridge was expected, and there was a two-fold increase as compared to the treatment plots. The controlled plots were cultivated once before soil sampling, and cultivation is known to stimulate mineralization of SOM (Peigné et al., 2007). Also, there was no plant N uptake in the control plots.

The low soil N levels at Kernen resulted in a green manure biomass of 1319 kg ha^{-1}, which was 73% lower than the average biomass at Lethbridge (4955 kg ha^{-1}). The green manure at Lethbridge benefitted from higher initial inorganic N and a longer growing season as compared to Kernen. The green manure intercrop at Lethbridge grew for 9 wk before termination, and at Kernen it grew only 6 wk. Greater dry matter production is desirable for a green manure used as a mulch in a low-till organic system. More biomass provides greater soil coverage, which conserves SOM and soil water, and suppresses weed growth (Morse and Creamer, 2006). Research at Virginia Tech University reported a cover crop must produce at least 6725 kg ha^{-1} to effectively suppress weeds as a mulch in an organic potato system (Morse, 2006). The use of high residue (>6000 kg ha^{-1} biomass) cereal/legume cover crops and equipment that evenly distributes the residue was recommended in the southern US to achieve effective weed control (Morse and Creamer, 2006). Low potential for mulch-based weed control exists with cover crop biomass <4000 kg ha^{-1}, and high weed suppression >8000 kg ha^{-1} (Morse and Creamer, 2006). These criteria may not be accurate for the Canadian prairies because colder temperatures and less moisture result in slower decomposition rates than the southern US. Weed suppression would likely be more effective at Lethbridge than Kernen. Soil coverage above 95% effectively suppresses weeds, while 75 to 95% coverage provides moderate suppression (Morse and Creamer, 2006). Based on observation, rolling was the only termination method that resulted in >95% soil coverage in the present study (Figure 4. 4). This observation must be verified with field measurements.

The increased soil coverage provided by the rolled-residue mat also conserves soil moisture (Ashford and Reeves, 2003; Kornecki et al., 2009; Olson-Rutz et al., 2010). When used to terminate a cereal cover crop, the roller-crimper increased soil water conservation as compared to herbicide-terminated treatments, even when the the kill efficacy was significantly lower than the herbicide treatments (Ashford and Reeves, 2003). The rolled plots in the present study were expected to have the highest soil moisture in May 2011; however, excessive precipitation received during the experiments at both research sites - 153% and 57% more in 2010 than the LTA at Kernen and Lethbridge, respectively - resulted in no treatment effects on soil moisture. Unfortunately, the moisture-conservating effect of the roller could not be assessed in this study.

Soil inorganic N was higher in the tilled treatments at both Kernen and Lethbridge in May following green manure termination. These results were expected, considering tillage and incorporation of crop residues increases mineralization (Peigné et al., 2007; Lupwayi and Burr, 2010). While soil inorganic N as affected by termination method was evident throughout the soil profile at Kernen, the differences were only evident within the top 30-cm of soil at Lethbridge. The elevated and similar inorganic N values with depth at Lethbridge (approximately 300 kg N ha^{-1} at 60 to 90 cm) may be due to a history of conventional management and fertilizer application. The accumulation of inorganic N at depth may have resulted from leaching. Risk of leaching is high in the spring after green manure incorporation, particularly with elevated precipitation and coarse-textured soil (Campbell et al., 1994). Lethbridge has a sandy clay loam texture and received 45% more precipitation than average from September 2010 following green manure termination until soil sampling at the end of June 2011. An organic study in Manitoba comparing green manure termination by rolling, tillage or a combination determined that reducing the number of tillage events reduced the risk of NO_3-N leaching (Vaisman et al., 2011). Using two tillage events instead of four to terminate a field pea/oat green manure reduced fall soil NO_3-N by nearly 40%, and NO_3-N concentration the following spring was significantly lower in the rolled than tilled treatments. In this study, soil inorganic N at 60 to 90 cm measured in the spring was significantly higher in the tilled plots than all other treatments at Kernen, and tended to be highest at Lethbridge.

Inorganic N measured in 2011 was lowest in the rolled treatments at both Kernen (0 to 15 cm) and Lethbridge (15 to 30 cm), which is consistent with previous organic research (Vaisman et al., 2011). The mowed plots tended to have higher inorganic N than the rolled crops, which was expected because mowed green manures degrade more quickly than rolled crops (Creamer and Dabney, 2002). The higher residue to soil contact increases residue mineralization. Cultivation in the rolled + fall tillage treatments was expected to increase soil inorganic N relative to the rolled-only treatments, but the values were not significantly different. Similarly, combining one tillage event with green manure termination by rolling did not significantly increase spring soil NO_3-N as compared to the rolled-only treatment in Manitoba (Vaisman et al., 2011).

Because the mineralization study analyzed the soil from within treatments, and did not include the surface residues from the rolled or mowed plots, it did not properly evaluate the treatments. However, N_{min} results between the tilled and surface-applied treatments did differ between the two sites. At Kernen, N_{min} was highest in the tilled treatment (27 kg N ha^{-1}), and lowest in the rolled + fall tillage treatment (7 kg N ha^{-1}). The rolled and mowed treatments were in the middle of the other treatment results. At Lethbridge, N_{min} was lowest in the tilled treatments (8 kg N ha^{-1}) and highest in the rolled treatments (18 kg N ha^{-1}). Differences between the two sites may be due to sampling time and substrate quality. Green manures with C:N's <15 degrade quickly and provide rapid release of plant-available N, while C:N's >25 can be immobilized and release nutrients slowly (Morse and Creamer, 2005; Olson-Rutz et al., 2010). The wider C:N (20:1) at Kernen resulted in slower mineralization of the green manure residue, and in May 2011 substrate remained available for N mineralization to continue. Inorganic N at Kernen was highest in the tilled treatment before the incubation began (38 kg N ha^{-1}), and at the end of 28 d (65 kg N ha^{-1}). In contrast, the green manure at Lethbridge had a narrower C:N (14:1), which resulted in rapid mineralization of the residue in the tilled plots and a decline in substrate availability. Initial inorganic N was higher in the tilled plots (22 kg ha^{-1}) than the other treatments, but the difference was not significant. Soil inorganic N determined after the incubation period was equivalent between the treatment plots at approximately 30 kg N ha^{-1}. The similarity in the initial and final inorganic N concentration in the tilled plots resulted in little N_{min}, while the surface-applied residues had higher N_{min}. Also, spring sampling at Lethbridge was not accomplished until 30 June 2011, and it is possible that most of the N from the residues had already been mineralized.

4.5 Conclusion

Termination by tillage of a field pea/barley green manure resulted in the highest soil inorganic N measured in the spring following termination at both sites. Termination by rolling tended to result in the lowest inorganic N within the top 30 cm measured in the spring. The addition of fall tillage after green manure termination by rolling (Treatment 3) did not significantly increase soil inorganic N levels over that of the rolled-only treatment at either site. Results of an incubation study to estimate 4 wk N_{min} varied with site. The C:N of the green manure at Kernen was 20:1 and N_{min} was highest in the tilled treatment, suggesting a slow and continual release of N from the residue. At Lethbridge, the C:N was 14:1 and N_{min} was lowest in the tilled treatment and highest in the rolled treatment. It was hypothesized that incorporation caused rapid release of nutrients from the high quality residues, and surface application slowed mulch decomposition and nutrient release. These results suggest synchrony between N release and crop uptake may be improved by leaving high quality residues on the soil surface, and incorporating those with wider C:N's to avoid extended N immobilization. If long-term soil fertility is the goal as opposed to immediate N availability, using green manures with wider C:N's and termination by rolling could be beneficial. However, N losses through ammonia volatilization must be considered when leaving high quality residues on the soil surface. The present study was limited by its short duration, and sampling time and environmental conditions affected the results. Longer-term studies in various soil conditions are recommended to better understand green manure N release in reduced-tillage systems. Also, proper assessment of N_{min} between treatments must include the mulch residue in the incubation.

5. SOIL MICROBIAL BIOMASS AND NUTRIENT AVAILABILITY IN A CONTINUOUS NO-TILLAGE ORGANIC SYSTEM

5.1 Introduction

Both no-tillage (NT) and organic agriculture have emerged as farming systems that enhance sustainability and soil quality (Liebig et al., 2004; Fließbach et al., 2007; Miller et al., 2008). With NT relying heavily on chemical inputs and organic management relying heavily on tillage for weed control, green manure termination and seedbed preparation, marrying the two practices may seem impossible. However, interest in adopting conservation tillage into organic agriculture is increasing with the intention of creating a more environmentally-sound farming system (Krauss et al., 2010). While reduced tillage or NT has been studied extensively in conventional systems, research in organic systems is still relatively new. The main focus of organic research is on reducing tillage during the green manure or cover crop phase of a rotation (Mirsky et al., 2009; Krauss et al., 2010; Vaisman et al. 2011). The roller-crimper is currently being used in several research trials across North America to replace tillage for green manure/cover crop termination. The roller-crimper is an implement that rolls over a crop and crimps the stems, killing the plant tissue and leaving the mulch anchored to the ground. Crop residue is uniformly distributed on the soil surface, and therefore provides weed suppression and retains moisture (Creamer and Dabney, 2002). Rather than *reducing* tillage, the concept of *eliminating* tillage in organics has rarely been explored.

In the Canadian prairies where dryland agriculture is practiced, NT has been adopted widely to reduce soil erosion, conserve soil moisture and enhance soil organic matter (SOM), which results in increased crop yields (Nielsen et al., 2002). The average area seeded with NT preparation in Alberta, Saskatchewan and Manitoba rose from 6% in 1991 to 43% in 2006 (Statistics Canada, 2007). In organic agriculture the pressures of weed control and soil fertility cannot be solved with chemical herbicides or fertilizers; therefore, researchers have speculated that continuous NT is likely impossible under organic management (Krauss et al., 2010). Continuous NT resulted in extremely poor crop yields in a 4-yr organic rotation in California, and mulch-based weed suppression was deemed unreliable (Drinkwater et al., 2000). In Virginia, a cover crop had to produce biomass of at least 6700 kg ha^{-1} and leave a 7- to 10-cm mulch layer to effectively suppress weeds in an organic potato system (Morse, 2006). The slower mineralization rate of the thick mulch could result in N shortages early in the growing season (Berner et al., 2008), whereas incorporation of residues with tillage facilitates N mineralization (Peigné et al., 2007). After only 1 yr of NT in a green manure-wheat organic rotation, Vaisman et al. (2011) reported lower spring available N and significantly lower wheat yields in NT compared to reduced or conventional tillage (CT) systems. Continuous NT in organic agriculture on the Canadian prairies has not been studied, and therefore the effect of NT on N and P availability and crop yield are unknown.

The accumulation of residues in NT systems can be a challenge because soil nutrients become stratified at the soil surface. Lupwayi et al. (2006b) reported more soil NO_3- and NH_4-N in NT than CT at 0 to 5 cm, but uniform results below that; Zibiliske et al. (2002) reported more bicarbonate-extractable P in the surface 8 cm of soil under NT than CT; and Salinas-Garcia et al. (2002) determined microbial biomass C (SMB-C) and microbial biomass N (SMB-N) to be highest at 0 to 5 cm under NT and decreased with depth, while SMB was uniformly distributed in the 0- to 15-cm layer under CT. Stratification of nutrients may reduce plant nutrient uptake by limiting accessibility to lower plant roots (Lupwayi et al., 2006b). Problems related to stratification can be solved with precise fertilizer applications in conventional agriculture; however, the issue of stratification in continuous NT organic agriculture has not been explored.

Organic systems rely on the biologically-mediated process of nutrient cycling from SOM to maintain soil fertility (Watson et al., 2002). Soil organic matter is closely tied to soil quality; declining soil quality results in decreased SOM. Soil organic matter decomposition is slowed in NT systems, which increases the longevity of the soil SMB (Beare et al., 1994). Soil SMB is used as an indicator of soil quality because it reacts more quickly to management changes than SOM, and an increase in soil SMB is considered an improvement of soil quality (Bending et al., 2004). Several studies report more SMB under NT surface soils than CT soils after only 3 to 5 yr (Carter and Rennie, 1982; Franzluebber and Arshad, 1996; Kandeler et al., 1999). In the long term, NT is considered to improve soil quality in conventional agriculture, and NT soils commonly have higher SMB at 0 to 5 cm than CT soils (Helgason et al., 2007).

Due to the large variation in soil SMB values, several microbial indices have been developed as more interpretable indicators of soil quality (Gonzales-Quiñones et al., 2011). The microbial quotient is the ratio of SMB-C to total organic C (SMB-C:TOC), and is considered to be an indicator of biological soil fertility. Generally, a lower microbial quotient indicates a more exploited soil (Sparling, 1992; Breland and Eltun, 1999). The ratio of SMB-C to SMB-N can indicate a change in the soil microbial population, with higher values indicating a higher proportion of fungi to bacteria in the SMB (Joergensen, 1995). After 3 yr of an organic rotation, Berner et al. (2008) reported a 15% higher microbial quotient and 4% higher SMB-C:SMB-N under reduced tillage with a chisel plough than CT with a mouldboard plough. Long-term NT has also been shown to shift microbial communities to fungal-domination in the surface layers (Frey et al., 1999), which could impact decomposition and mineralization rates in the long term.

The majority of research on NT agriculture is in conventional systems, and therefore, the purpose of this study was to compare the effect of continuous NT and CT 2 yr after green manure termination in an organic system. The objectives were to: i) determine the effect of 2 yr of continuous NT on soil N and P availability and oat N and P uptake; ii) determine if N and P stratification occurred in the surface soil layers after 2 yr of NT; and iii) compare SMB-C and SMB-N after 2 yr of NT and CT as indicators of long-term soil quality.

5.2 Materials and Methods

5.2.1 Site description

The field experiment was established in May 2008 at the Ian N. Morrison Research Farm (49°29′ N, 98°0′ W) in Carman, SMB. The soil is an Orthic Black Chernozem with a fine sandy loam texture. Average air temperature and total monthly precipitation at Carman during 2008, 2009 and 2010 are shown in Table 5.1. Average air temperature during the growing season (May-Aug.) was within 12% of the long-term average (LTA) in the three study years. Growing season precipitation in 2008 was 15% lower than the LTA, and in 2009 and 2010 was 23 and 42% higher than the LTA, respectively. The site had been managed organically since 2005 and the trial was established on land previously cropped to soybean (*Glycine max*).

5.2.2 Experimental design

A ‘long-term NT’ experiment was established in 2008 to compare NT and CT in an organic rotation. The overall experimental design involved a hairy vetch (*Vicia villosa*)/barley (*Hordeum vulgare*) green manure intercrop grown and terminated in 2008, a flax (*Linum usitatissimum*) crop in 2009 and an oat (*Avena sativa*) crop in 2010. This study reports on

Table 5.1 Mean monthly air temperature and total precipitation during the growing season for each year at Carman, SMB (MAFRI 2010, Environment Canada 2010). Long-term averages (LTA) from 1971 to 2001 at Carman are included (Environment Canada).

Year	May	June	July	Aug.	Growing season
Air temperature (°C)					
GM 2008	8.9	15.5	18.2	19.1	15.4
Flax 2009	8.5	15.4	18.0	17.1	14.7
Oats 2010	11.6	16.4	19.6	18.7	16.6
LTA	12.4	16.8	19.5	18.6	16.8
Precipitation (mm)					
GM 2008	33.6	84.4	37.6	54.8	210.4
Flax 2009	69.2	126.8	68.4	52.6	317.0
Oats 2010	159.2	73.2	48.0	138.4	418.8
LTA	52.1	76.2	65.0	49.5	242.8

samples taken during the oat year only. It was a simple experiment comparing two treatments: 1) NT using the roller-crimper; and 2) CT using a tandem disc. The experimental design was a randomized complete block design (RCBD) with four replicates. Individual plot size was 4 by 35 m. Dr. Martin Entz's research group from the University of Manitoba (U of M) was responsible for field preparation and maintenance.

All plots were cultivated with a field cultivator (International vibra shank) twice in spring 2008 before seeding the green manure intercrop. Hairy vetch (VNS) was seeded at 32 kg ha^{-1} and barley (cv. Ranger) at 93 kg ha^{-1} to a depth of 6 cm using a Fabro plot-disc drill. The green manure in all plots was rolled twice on 28 July 2008 to kill the barley. On 17 September 2008 the CT plots were tandem disced twice, and on 22 September the CT treatments were deep tilled to further incorporate the residues. On 25 September the NT plots were rolled to kill weeds and minimize snow trapping to facilitate winter-kill of the hairy vetch. In spring 2009 the CT treatments were cultivated and all plots were seeded to flax (cv. Bethune) at a density of 55 kg ha^{-1} to a depth of 6 cm with a Fabro plot-disc drill. The plots that were rolled in year 1 remained NT and were not rolled again after 2008. After flax was harvested the last week of August 2009 the CT plots were deep tilled, and then deep tilled again at the end of September. The CT plots were cultivated twice early April 2010 for seedbed preparation. All plots were seeded to oat (cv. Leggett) 8 April 2010 with a Fabro plot-disc drill at a density of 138 kg ha^{-1} and to a depth of 6 cm. To maximize weed suppression 69 kg ha^{-1} oat was seeded straight, and then another 69 kg ha^{-1} was seeded at a 45° angle. The oat was swathed on 3 August, harvested on 6 August, and all the plots were harrowed with a diamond harrow to spread the straw on 9 August. The CT treatments were tilled twice with a tandem disc on 9 August, and the second treatment remained NT. Results of the soil and plant samples are only reported for the oat year of 2010.

5.2.3 Soil sampling and analysis (2010)

Soil samples were collected by U of M staff on 17 and 18 May 2010 and sent under refrigeration (4°C) to Saskatoon. On 17 May surface (0 to 15 cm) soil cores were extracted from each plot using a small backsaver probe (2-cm diam.) and separated into 0- to 5-, 5- to 10- and 10- to 15-cm samples. Thirty samples were taken randomly within each plot and composited by depth. One of the 0- to 5-cm samples from each treatment became saturated with water during shipping; therefore, only three replicates were analyzed for gravimetric soil moisture, inorganic

N and P, soil organic C (SOC), and SMB. On 18 May four samples per plot were taken with a Dutch auger (4-cm diam.) at depths of 0 to 15, 15 to 30, 30 to 60, and 60 to 120 cm and composited by depth to be analyzed for gravimetric soil moisture and inorganic N and P. All samples taken in May were kept at 4°C until analyzed after shipment to Saskatoon.

On 17 August, approximately 10 days after oat harvest, soil surface sampling (0 to 5, 5 to 10, 10 to 15 cm) was repeated. A larger backsaver probe (3.5-cm diam.) was used and only eight samples were taken per plot and composited by depth. All samples were kept at 4°C until analyzed for gravimetric soil moisture, inorganic N and P, SOC and SMB.

Gravimetric soil moisture was determined on all soil samples by weighing 5 to 10 g moist soil, drying it for 48 hours at 110°C, and then re-weighing. Gravimetric soil moisture was calculated according to Eq. [5.1]:

$$\text{Gravimetric soil moisture (\%)} = \frac{\text{wet soil} - \text{dry soil}}{\text{dry soil}} \times 100 \qquad [5.1]$$

Soil NO_3^- and NH_4^+ of all soil samples in May and August were extracted with 2.0 *M* KCl (Maynard et al., 2008): 5 g of field moist soil was shaken with 50 mL 2.0 *M* KCl for 1 hr at 142 rpm on a rotary shaker, then filtered through VWR 454 filter paper (VWR International). Soil PO_4 was extracted by the modified Kelowna procedure (Ashworth and Mrazek, 1995): 3 g of dried soil was shaken with 30 mL Kelowna solution for 5 min at 160 rpm, then filtered through VWR 454 filter paper. All extracts were kept at 4°C until the concentrations were measured on a SmartChem (Westco Instruments, Inc, Brookfield, CT). Soil NO_3^- and NH_4^+ were summed and are referred to as “Inorganic N”.

Soil organic C was analyzed on dried and sieved (<2 mm) soil by combustion at 800°C using a LECO C632 Carbon determinator (LECO Corporation, St. Joseph, MI).

5.2.3.1 Soil microbial biomass

The chloroform-fumigation-extraction method (Voroney et al., 2008) was used to measure SMB-C and SMB-N. Soils were removed from 4°C storage and sieved through a 2-mm sieve in preparation for pre-incubation. Field capacity (FC) was estimated using a saturated soil column. Soil was placed in a 5- by 15-cm plastic column that was closed at one end with cheesecloth, and placed upright in a bucket of sand. The soil was saturated with water and the open end of the column covered with Parafilm®. After 48 h three 10 g samples were taken from within the column and gravimetric soil moisture of the three samples was determined according to Eq. [5.1]. An average of the three samples was calculated.

Gravimetric soil moisture was determined for each 0- to 5-cm sample. Four, 25-g dry weight equivalent subsamples of the sieved samples were weighed into 125 mL glass jars. All of the samples were adjusted to 60% FC by adding water, and then mixed. The glass jars were covered with Parafilm® and incubated at 25°C for 7 d to stabilize soil metabolism before fumigation (Voroney et al., 2008). The bottles were opened every 3 d to reintroduce oxygen into the system to prevent the development of anaerobic conditions, and to re-adjust moisture content. Two of the four subsamples were fumigated and the remaining were unfumigated controls.

Fumigation was carried out according to Voroney et al. (2008) in a desiccator attached to a vacuum pump using ethanol-free chloroform ($CHCl_3$). One set of duplicates was fumigated in a vacuum-sealed desiccator for 1 to 2 min with 50 mL $CHCl_3$. The desiccator was left sealed and in the dark for 24 h after fumigation. After 24 h the samples were evacuated with air from the vacuum pump system five times to remove residual $CHCl_3$.

Fumigated and unfumigated samples were extracted with 50 mL 0.5 M K_2SO_4. After shaking the jars for 1 h the soil suspension was filtered through Whatman™ GF-934-AH filter paper (GE Healthcare UK, Buckinghamshire, UK). The unfumigated samples were extracted immediately after the fumigated set was put in the desiccator for fumigation, and the fumigated samples were extracted after the 24 h fumigation period. The filtrate was frozen at -20°C until analysis for total organic C (TOC) and total N (TN) on a TOC-V modular machine (Shimadzu Corporation, Kyoto, Japan). Total organic C was analyzed on the TOC-V_{CPN} total organic C analyzer, and TN on the NTM-1 total N measuring unit (Shimadzu Corporation, Kyoto, Japan). The filtrates were diluted 50 times before analysis because the TOC-V is sensitive to high salt concentrations. Microbial biomass was determined according to Eq. [5.2] and [5.3]:

$$\text{SMB-C} = \frac{\text{TOC in fumigated samples} - \text{TOC in control samples}}{k_{\text{EC}}} \qquad [5.2]$$

$$\text{SMB-N} = \frac{\text{TN in fumigated samples} - \text{TN in control samples}}{k_{\text{EN}}} \qquad [5.3]$$

where k_{EC} = 0.35 and k_{EN} = 0.5 (Voroney et al., 2008) and are constants representing the efficiency of the extraction procedures.

5.2.4 Plant sampling and analysis

At harvest, oat aboveground biomass samples were hand-harvested from three 0.25 m^2 quadrats per plot by Dr. Entz's research group. The oat samples were dried at 70°C, ground on a Wiley Mill (Thomas Scientific, Swedesboro, NJ) and sent to Saskatoon. Total N and P concentration ($\mu g\ g^{-1}$) of the oat plants were determined by acid digestion (Thomas et al., 1967) and analyzed on the Smart Chem. Oat N and P uptake ($kg\ ha^{-1}$) were calculated according to Eq. [5.4]:

$$\text{N or P uptake (kg ha}^{-1}\text{)} = \frac{[\text{dry weight (g m}^{-2}\text{)}] \text{ x } [\text{N or P concentration } (\mu\text{g g}^{-1})]}{10^5} \qquad [5.4]$$

Oat was harvested with a small-plot combine and oat grain yield determined.

5.2.5 Statistical methods

Data was analyzed as a 1-way randomized complete block design using ANOVA in CoStat (CoHort Software, Monterey, CA). Termination method (rolling and tillage) defined the main effect of tillage regime (NT or CT). Tillage treatments were considered significant at $P < 0.05$. Means within treatments were compared using Tukey's HSD at the 5% level of significance.

5.3 Results

5.3.1 Soil data

Soil moisture measured to depth in May 2010 showed no treatment effects throughout the soil profile (Table 5.2). Gravimetric soil moisture averaged ~ 16% at 0 to 15 cm, ~20% at 15 to 30 cm and 30 to 60 cm, and ~22% at 60 to 120 cm. The estimated FC (33 kPa) at Carman, based on a sandy loam texture and 2.5% organic matter is 18% (Saxton and Rawls, 2006). Overall, soil inorganic N and P were unaffected by the NT and CT treatments (Table 5.3). The NT plots

Table 5.2 Mean gravimetric soil moisture (n=4) in the soil profile after two years of tillage treatments. Samples taken in May 2010 at the start of the oat growing season at Carman, SMB.

	Soil moisture			
	Depth (cm)			
Treatment	0-15	15-30	30-60	60-120
	-------------------- % -------------------			
No-till	15.4[†]	20.1	20.5	23.7
Tillage	17.7	19.3	19.4	21.8

[†] Means within a column not followed by letters are not significantly different at $P<0.05$ according to Tukey’s HSD.

Table 5.3 Mean inorganic N and P in the soil profile after two years of tillage treatments. Samples taken in May 2010 at the start of the oat growing season at Carman, SMB. Data are mean of four replicates.

	Soil inorganic N					Soil inorganic P				
	Depth (cm)					Depth (cm)				
Treatment	0-15	15-30	30-60	60-120	0-120	0-15	15-30	30-60	60-120	0-120
	---------------------- kg N ha^{-1} ----------------------					---------------------- kg P ha^{-1} ----------------------				
No-till	27.6[†]	17.5	24.9	36.5	106.5	27.9	8.1	**7.4b**	48.1	91.5
Tillage	25.4	13.3	19.1	32.6	90.4	21.9	7.5	**9.8a**	50.4	89.6

† Means within a column followed by different letters and bolded are significantly different at *P*<0.05 according to Tukey's HSD; means within a column not followed by letters are not significantly different.

tended to have higher amounts of inorganic N and P throughout the soil profile except at the 30 to 60 cm depth, where the CT plots had significantly higher inorganic P than the NT plots (Table 5.3).

Results of the surface soil 5-cm increments taken in May are presented in Table 5.4. Surface soil moisture measured in May was unaffected by tillage system, and tended to increase with sample depth (Table 5.4). Soil inorganic N and P were stratified with sample depth and decreased from the 0- to 5-cm to 10- to 15-cm depth. Microbial biomass C and N were also stratified and decreased with sample depth (Table 5.4). Microbial biomass C was slightly higher under NT (390.4 mg C kg^{-1}) than CT (366.2 mg C kg^{-1}), but the difference was not significant. The ratio of SMB-C to SMB-N increased with sample depth from 9.2 at the 0- to 5-cm depth to 12.5 at the depth 10- to 15-cm depth (Table 5.4). The microbial quotient was unaffected by tillage treatment and decreased with each sample depth, ranging from 1.4 to 0.9%. All of the results presented from the May sampling of the surface soil did not demonstrate stratification due to tillage system; the two systems behaved in the same way. Mean TOC was affected by tillage system ($P = 0.0388$); TOC was 3.4% for NT and 3.2% for CT (data not shown). Total organic C also decreased with depth, ranging from 3.5% at the soil surface to 3.1% at 10 to 15 cm (data not shown).

Soil moisture, soil inorganic N & P, and SMB-C&N measured in August after oat harvest were stratified with depth, and decreased from the surface to the 10- to 15-cm depth (Table 5.5). The interaction between tillage and sample depth was significant for soil inorganic N (Table 5.5). Soil inorganic N was significantly higher at 0 to 5 cm for the NT treatment than the CT treatment, but equivalent between the two treatments at other depths (Figure 5.1). Tillage treatment also significantly affected inorganic N; the amount under NT was 8.9 kg N ha^{-1}, but only 6.5 kg N ha^{-1} for CT (Table 5.5). As in the May samples, SMB-C was slightly higher for NT (455.4 mg C kg^{-1}) than CT (434.6 mg C kg^{-1}), but not significantly so. The ratio of SMB-C to SMB-N was stratified with depth, increasing from 10.6 at the surface to 14.4 at 10 to 15 cm (Table 5.5). The NT treatment had a slightly higher SMB-C:SMB-N than CT treatment, but the differences were not significant. The microbial quotient decreased from 1.8 to 1.0% with sample depth. Total organic C was also unaffected by tillage system and averaged 3.2% (data not shown).

Table 5.4 Mean surface soil moisture, soil inorganic N ($NO_3^-+NH_4^+$), soil inorganic P (PO_4), microbial biomass C and N (SMB-C/N), the ratio of SMB-C to SMB-N, and the microbial quotient as affected by sample depth. Samples taken in May during oat growth at Carman, SMB in 2010. ANOVA table showing probability level where effect of source of variation considered significant at P<0.05.

Factor	Treatment	Soil moisture	Soil inorganic N	Soil inorganic P	SMB-C	SMB-N	SMB-C:SMB-N	Microbial quotient[†]
		%	kg N ha^{-1}	kg P ha^{-1}	mg C kg^{-1}	mg N kg^{-1}		%
Tillage system *n*=9	No-till	19.3[‡]	7.7	20.4	390.4	36.4	11.2	1.2
	Tillage	17.7	8.3	20.7	366.2	37.3	10.5	1.1
Sample depth (cm) *n*=6	0 to 5	17.0	**9.9a**	**27.5a**	**491.6a**	**53.8a**	**9.2b**	**1.4a**
	5 to 10	18.3	**7.7b**	**23.3a**	**368.5b**	**34.1b**	**10.8ab**	**1.1b**
	10 to 15	20.2	**6.4b**	**10.9b**	**274.9c**	**22.7c**	**12.5a**	**0.9c**

Source of variation	---------- Probability (P) ----------						
System	0.1381	0.2921	0.9079	0.2628	0.7065	0.4065	0.6436
Depth	0.0728	**0.0036**[¶]	**0.0001**	**<0.0001**	**<0.0001**	**0.0160**	**0.0001**
System x Depth	0.8340	0.8515	0.8811	0.7850	0.5840	0.8992	0.7294

† Microbial quotient = (microbial biomass C/total organic C)*100.

‡ Means within a factor in the same column followed by a different letter and bolded are significantly different at P<0.05 according to Tukey's HSD; means within a factor in the same column not followed by letters are not significantly different.

¶ Bolded P values are significant at <0.05.

Table 5.5 Mean surface soil moisture, soil inorganic N (NO_3^-+NH_4^+), soil inorganic P (PO_4), microbial biomass C and N (SMB-C/N), the ratio of SMB-C to SMB-N, and the microbial quotient as affected by sample depth. Samples taken 10 d after oat harvest in August, 2010 at Carman, SMB. ANOVA table showing probability level where effect of source of variation considered significant at *P*<0.05.

Factor	Treatment	Soil moisture	Soil inorganic N	Soil inorganic P	SMB-C	SMB-N	SMB-C:SMB-N	Microbial quotient[†]
		%	kg N ha^{-1}	kg P ha^{-1}	mg C kg^{-1}	mg N kg^{-1}		%
Tillage system *n*=12	No-till	24.8[‡]	**8.9a**	5.5	455.4	37.5	13.2	1.4
	Tillage	24.1	**6.5b**	5.6	434.6	37.5	12.4	1.3
Sample depth (cm) *n*=8	0 to 5	**27.1a**	**11.6a**	**6.3a**	**641.9a**	**61.4a**	**10.6b**	**1.8a**
	5 to 10	**23.9b**	**7.1b**	**5.4b**	**403.1b**	**30.7b**	**13.3a**	**1.3b**
	10 to 15	**22.5c**	**4.5c**	**5.1b**	**289.9c**	**20.5c**	**14.4a**	**1.0c**

Source of variation		Probability (*P*)					
System	0.0738	**0.0026**	0.5532	0.1674	1.0000	0.1413	0.5636
Depth	**<0.0001**[¶]	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**0.0001**	**<0.0001**
System x Depth	0.2053	**<0.0001**	0.2874	0.9675	0.9593	0.6251	0.9329

† Microbial quotient = (microbial biomass C/total organic C)*100.

‡ Means within a factor in the same column followed by a different letter and bolded are significantly different at *P*<0.05 according to Tukey's HSD; means within a factor in the same column not followed by letters are not significantly different.

¶ Bolded *P* values are significant at <0.05.

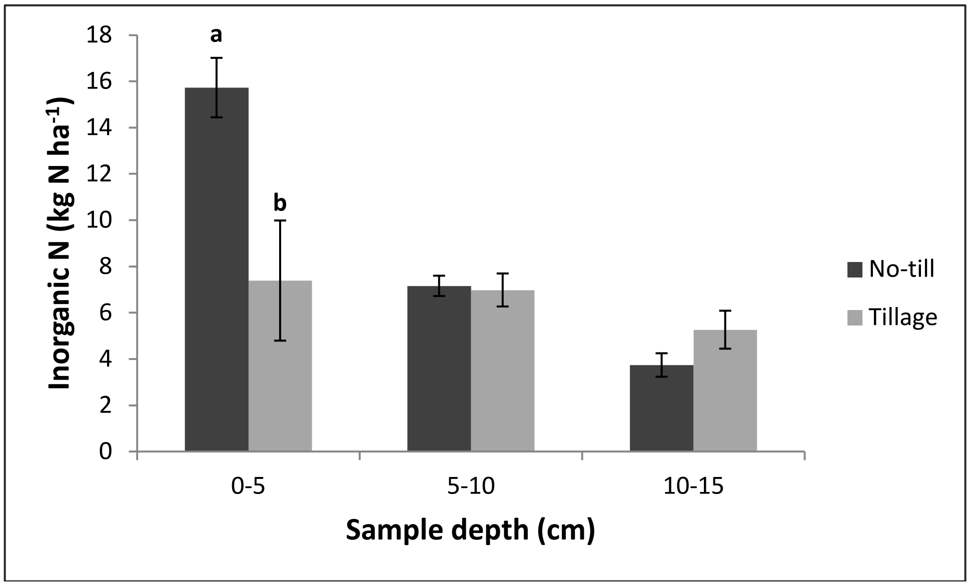

Figure 5.1 Soil inorganic N ($NO_3^- + NH_4^+$) measured 10 d after oat harvest (August 2010) at various soil depths as affected by tillage system at Carman, SMB. The interaction between tillage system and sample depth was significant (P<0.0001). Inorganic N at 0 to 5 cm was higher for no-tillage (15.7 kg N ha^{-1}) than the conventional tillage system (7.4 kg N ha^{-1}) according to Tukey's HSD (P=0.0096). Bars indicate standard error of means (n=4).

5.3.2 Plant data

At harvest**,** oat aboveground biomass, N and P concentration, and N and P uptake were not statistically different for the two treatments (Table 5.6). Oat biomass and N and P uptake tended to be higher for the tilled treatment, as did the grain yield. Oat yield was 2633 kg ha^{-1} in the NT treatments and 2996 kg ha^{-1} in the CT plots, but the difference was not significant.

5.4 Discussion

Spring available N and P and oat yield were expected to be lower in the NT plots as compared to the CT plots after 2 yr, but values were equivalent between the treatments. Tillage enhances nutrient availability in organic systems because it increases the surface area of residues and soil aggregates, which stimulates mineralization (Miller et al., 2008). Organic and conventional studies have reported nutrient deficits caused by a reduction in tillage (Drinkwater et al., 2000; Mahli et al., 2010; Blackshaw et al., 2010; Vaisman et al., 2011). In the spring following green manure termination by rolling or tillage, Vaisman et al. (2011) reported lower spring NO_3-N following NT management than CT management, which corresponded with lower N uptake in the following wheat crop. Similarly, studies in Saskatchewan report higher soil NO_3-N (0 to 15 cm) in the spring following a legume terminated by conventional tillage than by herbicide in a NT system (Malhi et al., 2007, 2010; Soon et al., 2001). Wheat grain yield the first year after alfalfa termination was 35% lower for NT than tilled treatments (Malhi et al., 2010). Flax yield in our Carman study measured in 2009, the first year after green manure termination, was not statistically different for NT (1894 kg ha^{-1}) and CT (2265 kg ha^{-1}) treatments (C. Halde, personal communication, 2011). In the second year following alfalfa termination by herbicide or tillage, Malhi et al. (2010) found no difference in soil inorganic N in the spring and no difference in canola yield. Similarly at Carman in 2010, continuous NT resulted in the same soil inorganic N and P, oat N and P uptake, and oat yield as CT. Lack of differences between treatments at Carman may be explained by the diminishing tillage effect over the course of the growing season. Although wheat N uptake was lowest under NT early in the season at all sites, by the soft dough stage Vaisman et al. (2011) found significant tillage effects at only one of three sites. Increased levels of available N later in the growing season has also been observed under NT in a sweet clover green manure system (Soon et al., 2001).

Table 5.6 Mean biomass, N and P concentration, and N and P uptake of oat aboveground samples as affected by tillage treatments. Oat data collected at harvest in August 2010 at Carman, SMB. Data are mean of four replicates.

Treatment	Biomass	N conc	P conc	N uptake	P uptake	Oat yield†
	kg ha^{-1}	---------- g kg^{-1}	------	kg N ha^{-1}	kg P ha^{-1}	kg ha^{-1}
No-till	3219.8‡	7.6	3.8	24.5	12.2	2633.0
Tillage	3880.8	7.4	3.8	28.7	14.4	2996.0

† Data collected by Dr. Entz's research group at the University of Manitoba.

‡ Means within a column not followed by letters are not significantly different at *P*<0.05 according to Tukey's HSD.

There are numerous benefits associated with NT management that can increase the sustainability of organic systems. No-till is primarily adopted to build SOM, which helps prevent soil erosion, increases water infiltration and soil stability, and sequesters C (Lal, 2007). In an organically-managed system, reducing the intensity of tillage by using a chisel plough instead of a mouldboard plough resulted in a 7% increase in SOC in 3 yr (Berner et al., 2008). However, SOC was not affected by the tillage regime change in Carman after 2 yr of continuous NT management. Research suggests that soils with high OM content are slow to change; average SOC at Carman ranged from 3 to 3.6%, while the average was closer to 2% in the Berner et al. (2008) study.

Soil moisture retention is another advantage of NT agriculture, and has been cited as a factor contributing to increased yield over CT (Nielsen et al., 2002; Teasdale et al., 2007). Because growing season precipitation at Carman in 2009 and 2010 was 23 and 42% greater than the long-term average (LTA), the moisture retention benefit of NT was not apparent and the crops flourished under both tillage regimes.

In NT-organic systems, cover crops or green manures are used as mulches for weed control. If grown and managed correctly, mulches can inhibit weed growth, reduce the risk of soil erosion by covering the soil, and reduce evapotranspiration (Ashford and Reeves, 2003; Olson-Rutz et al., 2010). The mulch laid down by a fall rye (*Secale cereale*) cover crop grown in North Carolina and terminated with a roller-crimper provided sufficient weed control when the rye biomass was above 9000 kg ha^{-1} (Smith et al., 2011). With less biomass (<6600 kg ha^{-1}), weeds were not controlled and yield poor following soybean (*Glycine max*). In a 4-yr organic rotation under NT management, Drinkwater et al. (2000) reported insufficient weed control from a hairy vetch mulch, and weed pressure was the primary cause of crop failure. While weed data was not collected at Carman, the plots were managed in an effort to promote crop competition against weeds (C. Halde, personal communication, 2011). The hairy vetch/barley green manure grown in 2008 had an end of season biomass of 7593 kg ha^{-1} and created a thick mulch for weed suppression (Figure 5.2). The flax and oat crops were sown as early as possible in the spring at a high seeding density to provide an advantage over the weeds (M. Entz, personal communication, 2010), and the residues provided significant ground cover (Figure 5.2).

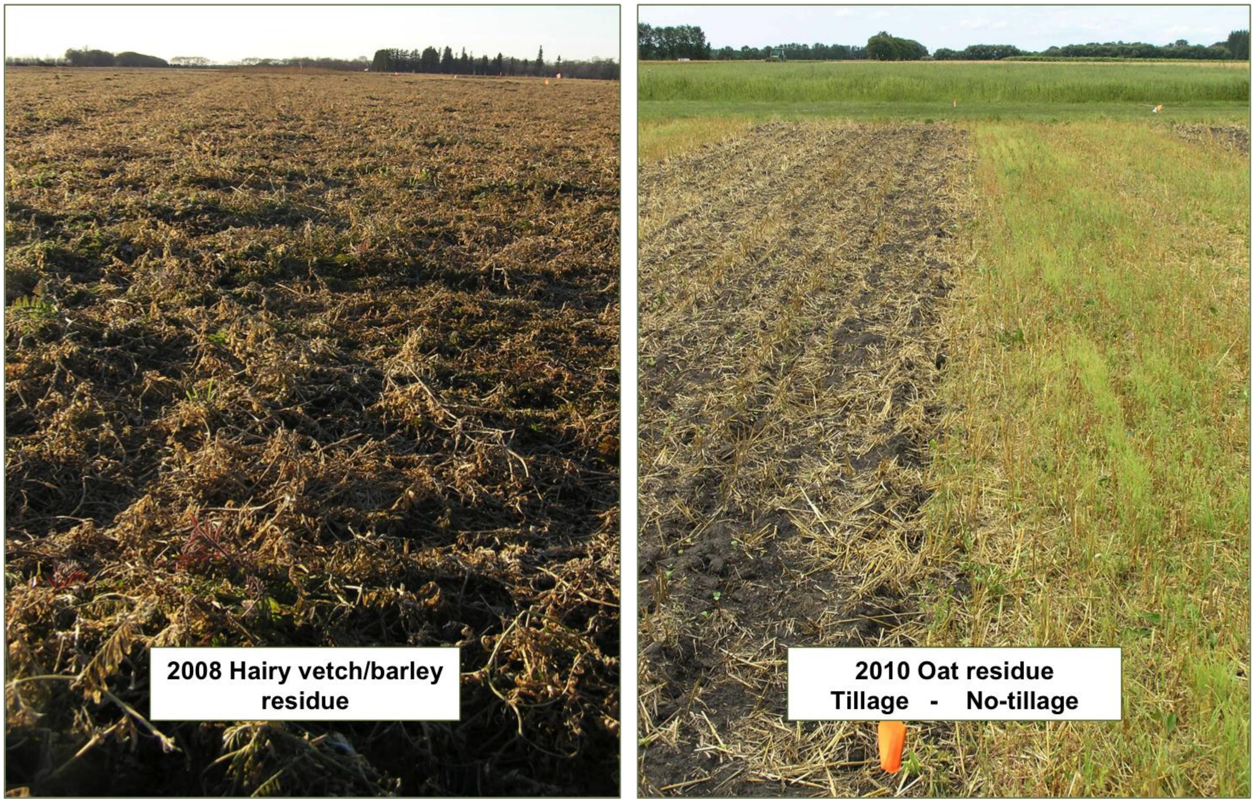

Figure 5.2 Hairy vetch/barley green manure residue in September 2008 after rolling with the roller-crimper at Carman, SMB. Oat residue 10 d after harvest in August 2010 in a tillage treatment (left) and no-tillage treatment (right) at Carman, SMB.

Soil samples taken from the top 15 cm in May and August of 2010 at Carman demonstrate stratification with sample depth of the measured soil properties, but not stratification as a result of tillage system. Stratification is often evident in NT soils, with soil nitrate-N (Lupwayi et al., 2006b), mineralized N (Kandeler et al., 1999), available P (Rasmussen, 1999), and SMB (Stockfisch et al., 1999) concentrated at the soil surface, while these soil properties are evenly distributed within the top 15 cm in CT systems. Soil inorganic N and P decreased with depth in the surface soil at Carman under NT and CT management. Inorganic N measured in August at the 0- to 5-cm depth responded differently to tillage regime, with higher inorganic N under NT management (15.7 kg N ha^{-1}) than CT (7.4 kg N ha^{-1}). Results in the third year of NT at Carman are consistent with results after 7 or 8 yr of NT management in a conventional rotation in northern Alberta. Lupwayi et al. (2006b) reported higher concentrations of inorganic N under NT compared with CT at the 0- to 5-cm layer, but similar N concentrations between treatments at lower soil horizons. Similar to the results at Carman, the interaction between tillage system and soil depth on soil inorganic P was not significant in Alberta, although P tended to decrease with depth under NT (Lupwayi et al., 2006b). Nutrient uptake by wheat was usually greater under NT in the conventionally-managed Alberta study, but oat N and P uptake at Carman tended to be higher in the CT treatment under organic management.

At Carman, SMB was affected by sample depth but not by tillage treatment after 2 yr of continuous NT. The decrease in soil SMB with depth was expected, considering SMB is generally higher near the soil surface (Helgason et al., 2007). Reduced physical disturbance in the NT plots was expected to increase SMB as compared to CT due to slower decomposition and reduced disturbance of fungal hyphal networks (Beare et al., 1994; Berner et al., 2008). Reduced tillage or NT tends to increase SMB only in the top 5 cm of soil as compared to CT (Stockfisch et al., 1999; Alvarez and Alvarez, 2000; Lupwayi et al., 2004b). The NT plots at Carman tended to have higher SMB-C values in May and August 2010, but differences were not more pronounced at the 0- to 5-cm depth as previous research has reported. Microbial biomass C was higher under NT than CT after 3 yr in a canola-wheat-barley-fallow sequence in northern Alberta, but the difference was not significant (Franzluebbers and Arshad, 1996). At the end of 6 yr in the same study, SMB-C was significantly higher under NT management to a depth of 20 cm and was 9% greater than the CT treatment (Franzluebbers and Arshad, 1996). Similarly, a study in Saskatchewan reported higher SMB-C to a depth of 10 cm in NT than CT after 4 yr (Carter and

Rennie, 1982). After 10 yr (Emmerling et al., 2007) and 6 yr (Gadermaier et al., 2010) of organic rotations, SMB and microbial activity increased in the 0- to 15- and 0- to 10-cm soil depth under reduced tillage as compared to conventional tillage. Microbial biomass may increase with NT management in comparison to CT in the long term at Carman.

Acosta-Martinez et al. (2011) reported no difference in soil SMB between CT and NT at 0 to 10 cm after 5 yr of a dryland agriculture rotation in Texas. The soil had a sandy loam texture and was in a semiarid climate, and the researchers suggested changes in SMB take longer in sandy, dry conditions. The NT organic system at Carman is also a sandy loam texture and in a fairly dry climate, which may explain the lack of difference between the treatments. However, the 2010 sampling year at Carman received more precipitation than average. Acosta-Martinez et al. (2011) reported differences in SMB after only 3 yr when comparing cropping systems instead of tillage regimes. For example, changing from continuous cotton (*Gossypium hirsutum* L.) to sorghum (*Sorghum bicolor*)-cotton, or including a winter cover crop, increased SMB-C and SMB-N by up to 50% in the first 10 cm of soil (Acosta-Martinez et al., 2011). Differences in SMB with tillage regime were reported in an organic study comparing reduced tillage with a chisel plough to CT with a mouldboard plough (Peigné et al., 2007). The chisel plough disturbed the soil to a 15-cm depth, while the mouldboard plough inverted the soil and worked to a depth of 20 to 30 cm. In the present study a tandem disc and a chisel plough were used, which disturbed the soil to a depth of 10 cm. The treatments at Carman may be too similar (i.e. same crop rotations and relatively shallow tillage) to result in SMB differences.

Alvarez and Alvarez (2000) reported no difference in total soil SMB at 0 to 5 cm under NT, but did find higher active SMB in the 0- to 5-cm layer under NT. Total soil SMB was measured with the fumigation-incubation method (Jenkinson and Powlson, 1976), and active SMB was measured according to the technique proposed by Van der Werf and Verstraete (1987) where glucose and yeast extract were added to the samples before incubation. Lupwayi et al. (2004) reported soil SMB to be a good indicator of SOC, while microbial activity was a better indicator of decomposition in soil. It is important to not only examine total SMB but also microbial indices as indicators of changes in soil quality. Microbial indices are ratios between biochemical properties that are more interpretable than the largely variable SMB results (Gonzalez-Quiñones et al., 2011), and are used as early indicators of SOM enhancement (Stockfisch et al., 1999). At Carman, SMB-C:SMB-N tended to be slightly higher under NT management, and in May the ratio was higher (*P*=0.0279) for NT (9.7) than CT (8.6) at 0 to 5 cm. The increased SMB-C:SMB-N under NT in May indicates a change in microbial community composition as compared to CT. High SMB-C:SMB-N is indicative of fungal-dominated communities with older and more stable organic matter. Research has suggested that conditions at the surface of NT soils (e.g., lower moisture, lower temperature, stratification) are more suited to fungi, and therefore become dominated by fungal biomass (Dighton, 2003; Pietikainen et al., 2005; Helgason et al., 2007). Greater fungal biomass in the soil may indicate a higher potential for C sequestration because fungi produce recalcitrant by-products and increase soil aggregate formation through hyphal networks (White and Rice, 2007).

In a canola-wheat-barley-fallow sequence under conventional management in northern Alberta, there were no differences in SOC at 0 to 5 cm, 5 to 12.5 cm, or 12.5 to 20 cm after 3 or 6 yr of CT, reduced tillage or NT (Franzluebbers and Arshad, 1996). The lack of difference was attributed to the similarity between C inputs of the different tillage regimes, and the initially high SOC content of the soil (3.7% average 0 to 20 cm). Similarly, tillage regime did not affect SOC in the third year of an organic rotation at Carman, where SOC averaged approximately 3.3%. Soil organic C differences have been detected after 6 yr when comparing CT wheat-fallow and a NT continuous wheat; the NT treatment had higher SOC (Campbell et al., 1989). Tillage regime can also affect the microbial quotient, which is an indicator of biological soil fertility. In an organic system the microbial quotient was 15% higher at 0 to 10 cm under reduced tillage (4.3%) than under CT management (3.7%) (Berner et al., 2008). The microbial quotients measured at Carman in 2010 were much lower, with values ranging from 0.9 to 1.8%. Microbial quotient typically ranges from 1 to 5% (Sparling, 1992); however a typical critical microbial quotient value has not been identified. Because soil SMB-C rarely exceeds 5% of SOC, this value could be used as an estimate of the attainable microbial quotient for increased soil quality (Gonzalez-Quiñones et al., 2011). Analyzing a range of soils in western Australia, Gonzalez-Quiñones et al. (2011) discovered that a microbial quotient of 5% was an appropriate attainable goal for soils with up to 1.2% SOC, but further increases in SOC were not followed by increases in SMB-C. For soils exceeding 1.2% SOC, a SMB-C value of 600 mg C kg^{-1} was suggested as a more attainable goal. The average SOC at Carman was approximately 3.5%, and SMB-C ranged from nearly 300 mg C kg^{-1} at the 10- to 15-cm depth to 650 mg C kg^{-1} at the 0- to 5-cm depth. These results indicate the surface soils at Carman attained the SMB-C goal proposed by Gonzalez-

Quiñones et al. (2011), but the low microbial quotient indicates a degraded soil. The average SMB-C reported by Berner et al. (2008) was 888 mg C kg^{-1}, with a SOC content of 2.2%. It is possible the long history of cultivation at the Carman site has reduced soil quality; however the SOC content remains high.

5.5 Conclusion

Results from the present study at Carman indicate that continuous NT is possible under organic management. Nutrient availability and crop yield at Carman were not affected by tillage treatments, confirming that NT can be implemented without reducing productivity in the third year of an organic rotation. Soil nutrients, SMB, and SOC were stratified with sample depth, but for the most part were similar for both tillage systems. Considering that most studies reporting nutrient stratification in NT systems are long-term, it is likely stratification due to NT is in the early stages at Carman. When using soil SMB and the derived microbial indices as indicators of soil quality, tillage cannot be said to reduce soil quality in this organic system because the microbial measurements were statistically equivalent between the treatments. There is evidence that SMB-C and SMB-C:SMB-N under NT may increase in the long term. The low microbial quotient values in the present study as compared to other organic studies may indicate low soil quality at Carman.

6. SYNTHESIS AND MANAGEMENT IMPLICATIONS

Organic agriculture has traditionally been associated with environmentalism and sustainability due to the use of on-farm nutrient cycling and the absence of agrochemicals. The intensification of production on conventional grain farms in the second half of the 20th century tended to degrade soil quality, while soil quality improved under organic management. After more than 30 yr under conventional and organic management, soil organic matter (SOM), soil moisture, enzyme activity, and microbial biomass increased in an organic winter wheat system as compared to the conventional treatment (Reganold et al., 1987). Improved soil quality was attributed to higher organic matter inputs and diverse rotations under organic management (Reganold et al., 1987). Conventional practices have changed, however, and producers have widely adopted reduced and no-tillage (NT) management in the Canadian prairies (Statistics Canada, 2007). No-till increases soil physical, chemical and biological quality, including enhanced SOM and soil organic C (SOC) fractions (Malhi et al., 2008). There is skepticism whether organic systems can match the soil quality of conventional NT systems, as the benefit of organic matter addition in organic agriculture may be offset by the use of tillage (Teasdale et al., 2007). Some studies report increased SOM, SOC, or potentially mineralizable N (N_0) in organic systems compared to NT (Marriott and Wander, 2006; Teasdale et al., 2007; Miller et al., 2008), while others demonstrated no soil quality differences between the two management systems (Wander et al., 2007). A survey of farms across Saskatchewan reported lower average SOM levels on organic farms than typical levels measured on conventional farms in the same soil zone (Buhler et al., *In* Knight et al., 2010b). It is uncertain whether conservation tillage is necessary in an organic system, but the benefits of conservation tillage experienced by conventional producers are undeniable. Organic crop production depends on nutrient transformations in the soil, which are governed by SOM. Therefore, a key question is, “will reducing tillage improve the sustainability of organic cropping systems?”

Reducing the *intensity* of tillage (reduced inversion and depth) positively impacted SOM, biological indicators of soil quality, soil moisture retention, crop yields, and weed control in several organic studies (Emmerling, 2007; Teasdale et al., 2007; Berner et al., 2008; Gruber and Clupein, 2009; Gadermaier et al., 2010; Krauss et al., 2010). It is worth noting that some of these studies used compost (Berner et al., 2008), animal manure (Emmerling, 2007), or both (Gadermaier et al., 2010) as soil amendments, which increase SOM levels as compared to legume-dependent rotations (Fließbach et al., 2007). However, results have not been as successful when the frequency of tillage is reduced or eliminated, due to weed pressure and delayed N mineralization (Drinkwater et al., 2000; Peigné et al., 2007; Miller et al., 2008; Vaisman et al., 2011). Use of the roller-crimper to reduce tillage has proven most successful in the relatively warm and moist climates of the southern United States as compared to western Canada. High-biomass cover crops can be grown over the winter, and in one pass in the spring the cover crop is rolled and a crop is direct-seeded into the mulch (Mirsky et al., 2009; Mischler et al., 2010; Smith et al., 2010). Organic producers in the Canadian prairies are limited by short growing seasons and cold winters, and must rely on annual green manures that are terminated early in the summer to conserve soil moisture (Zentner et al., 2004).

Three short-term studies were presented in this work investigating reduced tillage in organic grain systems on the Canadian prairies. A reduction in tillage was accomplished to varying degrees, and was defined by replacing tillage for green manure termination with alternative low-disturbance methods (rolling and mowing). The general objectives were to determine the effect of reduced tillage on soil moisture, soil nutrient availability, soil SMB, and subsequent crop uptake and yield. The first study at Kernen, SK and Vonda, SK focused on the effects of termination timing and termination method of field pea (*Pisum sativum*) and faba bean (*Vicia faba*) green manures in a green manure-spring wheat (*Triticum aestivum*) rotation. The second study at Kernen and Lethbridge, AB examined the effect of termination method of a field pea/barley (*Hordeum vulgare*) green manure on soil inorganic N the following spring. The second study complemented the first because the same termination methods were used (tillage, rolling, mowing), but a green manure intercrop was used and no fall or spring cultivation occurred. Hence, an indirect comparison of a legume-only and legume/cereal green manure with different termination methods was possible. Finally, the third study at Carman, SMB took reduced tillage beyond the green manure year and evaluated the effect of 2 yr of continuous NT on soil nutrient availability, SMB and oat (*Avena sativa*) uptake. Including this study provided insight into the effects of organic NT.

Tillage was successfully reduced in the present study by replacing green manure termination by tillage with the roller-crimper or flail mower. Specifically, tillage was reduced by one third in the field pea-wheat system in Saskatchewan (Chapter 3), and eliminated completely at Carman (Chapter 5), without negatively affecting grain yield. Termination of field pea by rolling also decreased weed density measured in the fall at Kernen. The impact of green manure termination on soil moisture could not be properly measured in this study due to the excessive precipitation received in 2009 and 2010; however, it is likely that rolling would conserve soil moisture in drier years because the soil is left covered from mid-July until at least mid-October (Chapter 3) or through the winter (Chapter 4 & 5).

Overall, the effect of green manure termination on short-term inorganic N was dependent on green manure quality (C:N). Termination of high quality green manures (C:N ~15:1) with tillage resulted in rapid N mineralization, and likely did not contribute significantly to the SOM pool. Tillage of field pea at Vonda and faba bean at Kernen resulted in the highest level of soil inorganic N measured in the fall following termination, but tillage did not result in the highest subsequent wheat yield. Similarly, the field pea/barley green manure at Lethbridge had a C:N of 14:1 and resulted in the highest inorganic N measured the following spring, but resulted in the lowest N_0. These results demonstrate that tilling high quality green manures can provide rapid nutrient release, but the release may be asynchronized with crop uptake. In annual systems on the Canadian prairies, tilling green manures in the summer and fall leaves mineralized NO_3-N susceptible to loss through leaching and denitrification (Campbell et al., 1994, Watson et al., 2002). This is of particular concern under above normal moisture conditions.

To improve the synchrony of nutrient release/uptake and reduce the risk of nutrient loss, organic producers could increase the C content of their green manures or leave residues on the soil surface. At Kernen, the C:N of field pea was wide (23:1) and tillage resulted in the lowest fall inorganic N, likely due to N immobilization. However, the subsequent wheat yield was equivalent between the termination treatments at Kernen, indicating sufficient nutrient release over the season from the tilled treatment. In the second study at Kernen, the field pea/barley C:N was 20:1 and tillage resulted in higher 4 wk N_{min} than the other treatments. These findings are consistent with the general criteria that residues with C:N <15:1 are rapidly mineralized and residues with C:N ~25:1 are immobilized (Watson et al., 2002; Morse and Creamer, 2006). Surface-placed residues are also expected to release N more slowly than incorporated residues (Lupwayi et al., 2006a), as was verified in the first and second study. Termination of the field pea/barley green manure at Lethbridge resulted in the highest 4 wk N_{min}, indicating improved synchrony of N release from a high quality residue. Leaving residues on the soil surface increases the risk of N loss through volatilization (Janzen and McGinn, 1991). Ammonia loss from a pea/oat green manure after termination in Manitoba was higher when the green manure was rolled and left on the surface rather than tilled into the soil; however, the losses were minimal, averaging ~7% of the original green manure biomass N (Vaisman et al., 2011). In contrast, termination by rolling reduced the risk of nitrate leaching through the soil profile by 40% as compared to the tilled treatment (Vaisman et al., 2011). The added benefits of reduced soil erosion, soil moisture conservation, and weed suppression from green manure mulches likely outweighs losses through volatilization. Balancing these factors depends on the soil and climatic conditions of a particular system, which exert a strong influence on the rate and pattern of decomposition and N release (Franzluebbers, 2004).

The study in Carman confirms that with careful management (high crop seeding density early in the year, large biomass production, adequate soil cover), tillage can be eliminated from a system for at least 3 yr. However, whether NT *benefitted* the rotation at Carman is unclear. When using soil SMB as an indicator of soil quality, tillage did not reduce soil quality at Carman because, for the most part, the microbial measurements were equal between the treatments. There was a slight tendency towards higher inorganic N and SMB-C in the NT plots, suggesting beneficial long-term effects. However, the flax and oat yields at Carman tended to be lower for the NT treatment than the CT treatment. Although the difference was statistically insignificant, the difference may increase in the long-term due to weed pressure.

Researchers are not optimistic about the future of NT organic in the long term, and it is believed that some form of intermittent tillage will be necessary for weed control (Peigné et al., 2007). To obtain the benefit of NT, such as increased SOM and sequestered C, it must be practiced over the long term (Six et al., 2004). Conversion from plough tillage to NT is recommended for C sequestration; however, NT may not be suitable for regions with slow soil-warming in the spring, and serious perennial weed problems (Lal, 2011). A study in Saskatchewan reported that the C sequestered under NT is stored as particulate organic matter (POM) in the sand-size fraction (Angers et al., 1993), and this fraction is rapidly mineralized after a tillage event (Stockfisch et al., 1999). A modeling study estimated significant losses in SOC (up to 11%) in NT systems after one tillage event, and the losses increased with the frequency of tillage (Conant et al., 2007). However, the effects of introducing cultivation as compared to ploughing were much less severe, and reduced tillage that includes only biannual cultivation could realize as much as 80% of the C gains as strict NT (Conant et al., 2007). Similarly, a study in Spain measured little impact on TOC and SMB in the 0- to 5-cm layer with a chisel plough after 8 yr of NT, but a mouldboard plough had detrimental impacts on soil quality (Melero et al., 2011).

The question then remains, "how practical is NT or reduced tillage for organic agriculture, and is it necessary?" Likely, NT is not necessary for organic agriculture and is not practical. In the Canadian prairies producers struggle with perennial weed problems, and suffering yield loss due to weed pressure will not increase the sustainability of a system. Reducing both the intensity and frequency of tillage would benefit the soil quality and economics of prairie farms. The roller is a more fuel- and labour-efficient implement for green manure termination than tillage or mowing (Creamer and Dabney, 2002; Bernstein et al., 2011). The need for short-term nutrient availability and long-term soil fertility may be balanced in organic systems through the introduction of reduced tillage practices. Combining green manure termination by rolling, mulch-based weed control, and intermittent cultivation tillage would increase the SOC and SOM content of soils, which will improve long-term soil fertility. The roller may prove impractical due to inaccessibility and the number of passes needed. A farmer will not be interested in an implement that needs three passes to do the job of one pass with a tandem disc. In this case, mowing offers a viable reduced tillage option, and resulted in the highest wheat yield at one of the sites in this study. If producers are more concerned about N mineralization than mulch-based weed control and increasing SOC content, flail mowing green manures is a good alternative.

Limitations and future research areas

The main limitation of the field studies was the lack of control plots. Summerfallow control plots are used as 'checks' in organic research on the semi-arid prairies, where green manure-wheat cropping sequences rarely perform as well as summerfallow-wheat sequences. Performance of the green manure systems amongst themselves, and also in comparison to summerfallow would have strengthened the applicability of the results to organic producers. Without summerfallow or continuous wheat control plots it was difficult to judge how soil properties changed throughout the experiments, which was particularly evident in the Kernen/Vonda study. It was not possible to determine whether green manure termination timing truly affected soil inorganic N and soil moisture, or if the decline in N and moisture throughout the summer was natural. A control plot may have clarified this issue. Instead of control plots, the tilled green manure plots were considered the ‘control’ because it is the conventional termination practiced. A summerfallow control was included at Lethbridge, which clearly demonstrated the effect that tillage had on SOM mineralization.

The Kernen/Vonda study would have benefitted from a rolled- or mowed-only treatment, as opposed to cultivating all of the plots in the fall and spring. With a rolled-only treatment, or more combinations of rolling and tillage, N availability over time could have been measured. Following the experimental protocol, only fall sampling in the first year measured the pure treatment effects. Similarly, lack of direct comparison between legume-only and legume/cereal green manures in the same experiment was a limitation. With conditions varying greatly between sites and years, a comparison between the Kernen/Vonda study and the Kernen/Lethbridge study was not possible. The field conditions were also not typical with all of the precipitation received in 2009 and 2010. For this reason the effect of green manure management (timing and method) on soil moisture could not be analyzed.

Considering the most popular green manure used in the Canadian prairies is biennial sweet clover (*Melilotus officinalis*) (Knight et al., 2010a), future research should be conducted on the use of the roller for sweet clover termination. Sweet clover typically takes several tillage or mowing operations to terminate (S. Gunther, personal communication), and termination by rolling may be unsuccessful. On the other hand, sweet clover produces a large biomass (Blackshaw et al., 2010), and rolled sweet clover mulches may improve weed control over other termination methods. As a biennial, sweet clover keeps the ground covered longer than annual green manures, and rolling would create a more effective ground cover that could be direct seeded.

Determining optimal C:N’s that balance short- and long-term soil fertility is another future research area. Assumptions that C content would increase in a legume/cereal green manure were not confirmed in the present study. The C:N of the field pea/barley green manure in the second study was actually lower than the field pea green manure in the first study. Further experimentation with multiple green manure mixtures within the same study, and the effect of termination method on nutrient availability over time would be interesting. Asynchrony of nutrient release and uptake is a negative environmental impact of agriculture (Crews and Peoples, 2005), but it is also difficult to manage with organic residues. Results from this study appear to suggest that higher C:N and surface-placed residues slows mineralization in a positive way. Relying on soil inorganic N levels measured at one point in time is not a reliable prediction of nutrient availability in an organic system. However, it is the simplest tool available for producers on which to base their management decisions. If surface-placed residues result in lower soil inorganic N in the fall or spring, a producer is likely to rely on tillage instead. Long-term trials of reduced tillage and NT, including varying uses of cultivation at varying times (fall and spring), would help organic producers make informed management decisions.

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