Role of Green Manure Options in Organic Cropping Systems

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ABSTRACT

On the Canadian prairies, organic production generally includes the use of annual green manure (GrM) crops, which are terminated using tillage to add nutrients and organic matter to the soil. However, in a GrM plough-down year, farmers face loss of income. As an alternative to growing traditional GrM crops, legumes can be grown alone or intercropped with cereals and harvested as green feed forage (GF) for use on-farm or for sale to other producers without depleting soil nitrogen (N) for the subsequent crop. We hypothesized that the GF system would have similar biomass, and N yield, and ultimately would return N into the soil. Furthermore, by intercropping a legume with a cereal, biological N_2-fixation will be enhanced in the legume.

Field experiments, conducted over two years, were established at Vonda and Delisle, Saskatchewan, Canada. The experiment was conducted using a randomized complete block design (RCBD) with 16 treatments and four replicates in which field pea (*Pisum sativum* cv 40-10 silage pea), oat (*Avena sativa* L.cv AC Morgan), and triticale (X *Triticosecale* Wittmack cv Pika) were grown alone or in combination and managed as GrM or GF. Wheat and tillage fallow served as cropped and uncropped controls, respectively. The tillage fallow-control system was tilled twice in the growing season using a small tractor disc. The intercropped oat was seeded at three densities (50, 100, and 150 plants m^{-2}) to determine whether increasing cereal density stimulated N_2-fixation in the field pea.

The GrM system was sampled and incorporated (when the field pea was at full bloom) two weeks earlier than the GF system. Consequently, at both sites, all treatments in the GF system consistently yielded more dry matter and accumulated more N than treatments in the GrM system. At the Delisle site, where percent nitrogen derived from the atmosphere (%Ndfa) was compared, increasing cereal density did not increase N_2-fixation in both management systems. However, pea in the GF system accumulated more than twice the amount of N (kg ha^{-1}) from fixation as compared to pea in the GrM system, presumably because of the longer growth period. Wheat grown following the GrM treatments produced more biomass and accumulated more N than wheat following the GF treatments. Wheat grown after the monoculture field pea as a GrM had greater

yield than all treatments. As well, the GrM system returned more N to the soil than did the GF system. The extra two weeks of growth in the GF system resulted in the extraction of significant amounts of nutrients and probably moisture from the soil, which adversely affected yield and nutrient composition of the following wheat crop.

Although organic farmers may lose income in the plough-down year, on a long-term soil sustainability basis, the GrM system is a better option than the GF system as it returns nutrients to the soil, thus providing improved plant biomass, and N accumulation of subsequent crops. However, organic farmers growing GF for hay may benefit from the increased productivity of this system on a short-term basis. Thus, farmers pursuing GF options may need to adopt other means of sustaining soil productivity on a longer term. The tilled fallow-control system resulted in high amounts of biomass and N accumulation by the subsequent wheat crop, probably due to the fact that there were no nutrients taken up in the previous year and moisture was conserved in these treatments. However, this system may have less long-term benefits compared to the GrM regime, as no nutrients are returned through ploughing down a crop.

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DEDICATION

This thesis work is dedicated to my deceased Grandfather, Simon Marufu Mavenyengwa and my living Grandmother, Elizabeth Marufu for teaching me how to work with plants and soils since my childhood and for imparting in me the importance of soils and agriculture to humanity.

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LIST OF ABBREVIATIONS

AAFC	Agriculture and Agri-Food Canada
AAFRD	Alberta Agriculture, Food and Rural Development
BD	Bulk density
BNF	Biological Nitrogen Fixation
C	Carbon
^{o}C	Degrees Celsius
CEC	Cation exchange capacity
cm	centimetre
COG	Canadian Organic Growers
d	days
DAP	Days after planting
df	degrees of freedom
EC	Electrical conductivity
FAO	Food and Agriculture Organization
g	gram
GrM	Green manure
GF	Green feed forage
h	Hour
ha	Hectare
K	Potassium
kg	Kilogram
m	Metre
mS	Millisiemen
N	Nitrogen
N_2	Di-nitrogen
N_2-fixation	Nitrogen fixation
%Ndfa	Percent nitrogen derived from the atmosphere
OM	Organic matter
Δ	Delta
P	Phosphorus
SAF	Saskatchewan Agriculture and Food
SK	Saskatchewan
SOM	Soil organic matter
μg	Microgram

1 GENERAL INTRODUCTION

Farming on the Canadian prairies and elsewhere in North America and Europe has primarily focused on increasing productivity while reducing labour costs through technological advancements. The use of capital inputs such as fossil fuels, chemical fertilizers and pesticides, patented genetic material, and machinery has played a key role in helping farmers achieve their goals, which include higher crop yields (Beckie, 2000). Despite these milestones achieved in the industrialization of prairie agriculture, there have been negative impacts including loss of soil and water quality, biodiversity, and natural habitat, as well as depletion of fossil fuels and climatic change (Matson et al., 1997).

Other problems associated with increased mechanization and widespread use of certain agrochemicals has been linked to health problems faced by farmers and associated workers. For example, a case study revealed that exposure to certain pesticides and fungicides increased the incidence of cancer related diseases such as non-Hodgkin lymphoma in most western countries (Hardell and Eriksson, 2000). It is such health concerns and other factors including lower crop input costs, good environmental and soil management, and emerging diversified markets that have aroused interest in farmers shifting to agricultural production alternatives like organic farming (Beckie, 2000; Entz et al., 2001).

In comparison to conventional farming, organic farming limits the use of synthetic pesticides and fertilizers. In organic systems, farmers aim to achieve sustainability through their commitment to farming as natural systems (Welsh, 2007). As a result of this commitment, farmers increase crop and soil biota diversity that are important in maintaining soil fertility and structure (Hansen et al., 2001). In Canada, organic agriculture has grown significantly from 1174 certified producers in 1992 to 3618 in 2005. As of 2005, Saskatchewan had the highest number of certified organic producers in the country, standing at 1230 (AAFC, 2006).

Although there are environmental benefits associated with organic production, studies in Canada and elsewhere have reported reduced yields and increased weed and pest problems when farmers convert from conventional to organic farming. Crop yields under organic production rarely return to the levels achieved when conventional fertilizers and pesticides were used (Munn et al., 1998).

A long-term rotational study at Indian Head, SK, plots in which conventional nitrogen (N) and phosphorus (P) fertilizers were not used had significantly lower grain yields than fertilized plots after 15 years (Campbell et al., 1993). When perennial forages or annual legume crops were included in the rotation, crop yields improved, but did not reach to the levels of the conventional treatments, thus farmers may incur economic losses (Campbell et al., 1993).

Organic farming depends mainly on soil organic matter (OM) and biological activity as major nutrient suppliers in the soil and this, in turn, is dependant largely on the incorporation of plant biomass. Organic matter decomposes to release nutrients that are taken up by subsequent crops (Hendrix et al., 1986). The size and composition of the soil microbial biomass can affect the rate of decomposition of organic matter (Parker, 1990).

The benefits of growing annual legumes or legume-cereal intercrops in organic farming are well documented (Fujita et al., 1992; Fowler et al., 2004; Cherr et al., 2006). Legume and non-legume crops can be grown and incorporated before maturity to introduce N into the soil. Crops that are tilled back into the soil while they are still green are termed green manure (GrM) crops.

Intercropping legumes with cereals is thought to stimulate competition for soil N; the intensity of competition is dependent on the supply of soil N and the densities of plants (Corre-Hellou et al., 2006). For instance, as N levels in the soil are depleted by intercrops, through the NO_3^--N sparing effect of the pulse crop component, the soil N is taken up by the cereal component whereas the pulse crop component fixes N from the atmosphere (Szumigalski and Van Acker, 2006), as well as N supplied to the cereal component by the field pea through N_2-fixation (Corre-Hellou et al., 2006). Nitrogen sparing is reduced competition for soil NO_3^--N between the legume and cereal components. It is assumed that the legume component fixes N from the atmosphere thus, effectively "sparing" soil N sources, whereas the cereal derives its N from the soil. A study conducted by Hauggaard-Nielsen et al. (2007) concluded that pea-barley intercrops used N sources 20 to 30% more efficiently than their monoculture counterparts.

Despite the widespread use of GrM crops in organic cropping systems (Organic Farming Research Foundation, 2004 as cited by Cherr et al., 2006), there is still uncertainty over which GrM crop species or combinations are most productive (Cherr et al., 2006). One problem with the use of GrM crops is the loss of income faced by farmers from the crop in the plough-down year. One alternative may be to grow legume-cereal cover crops and harvest the above-ground biomass as green feed forage (GF) for hay or for sale rather than ploughing down.

The objectives of this research study are to:
(i) compare the productivity of several GrM and GF management options with respect to their biomass yields and nutrients returned into the soil, (ii) evaluate whether increasing cereal density enhances N_2-fixation in legume-cereal intercrops, (iii) compare the impact of GrM and GF options on subsequent wheat yield and soil N levels following harvest.

The hypothesis of this study was that the GF system would have similar biomass, and N yield, and ultimately would return N into the soil, as the GrM system.

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2 LITERATURE REVIEW

2.1 Nitrogen

Nitrogen is a major nutrient required in large amounts by arable crops (Jarrell, 1990). Although N is one the most abundant elements on earth, its complex chemical, physical, and biological transformations in the soil, together with its vulnerability to losses by gaseous emissions and leaching, makes it probably the most difficult nutrient to manage in many agricultural systems (Fowler et al., 2004).

Nitrogen is one of the major nutrients needed for crop growth and is required for several functions within the plant. Production of high quality protein-rich food is largely dependent on sufficient N. Nitrogen is a key component of amino acids, which are used to assemble proteins and nucleic acids (Havlin et al., 1999). As well, N is found in the chlorophyll molecule, is required in carbohydrate utilization, is contained in enzymes, and is known to stimulate root development and activity (Olson and Kurtz, 1982).

In the soil, N occurs either in inorganic or organic forms. About 95% of the N in the top soil is present in the organic form (Havlin et al., 1999). Inorganic forms of N in the soil include: nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), nitrous oxide (N_2O), nitric oxide (NO), and dinitrogen gas (N_2) (Young and Aldag, 1982). Of these, NO_3^- and NH_4^+ are most important to plants as they are absorbed by plants from the soil (Havlin et al., 1999).

The decomposition of soil organic matter together with N fertilizer application ensures availability of these N forms (Havlin et al., 1999). All nutritional N requirements by humans come directly or indirectly from plants. However, since the 1970s, management of N inputs into agricultural systems has become a contentious issue, thus the need for a sustainable approach to the management of N requirements (Vance et al., 2000).

2.2 Organic Production

In certified organic production, the use of inorganic fertilizers, pesticides, fungicides, and synthetic growth hormones is prohibited. On the Canadian prairies and elsewhere organic farmers are faced with a major challenge of potential depletion of mineral reserves such as N (Welsh, 2007; Fowler et al., 2004; Parfitt et al., 2005). Other concerns include disease and weed suppression and lower crop yields experienced by farmers when they convert from conventional to organic farming (Entz et al., 2001), as well as economic factors that include higher costs for labour, and management of GrM crops as fertilizers (Becker et al., 1995). However, in its various forms, organic farming is seen by many as a sustainable alternative to conventional farming as both OM content and biological activity are usually higher in organic systems than in conventional systems (Condron et al., 2000; Hansen et al., 2001).

A 21-year European study examining the agronomic and ecological performance of livestock based bio-dynamic, bio-organic, and conventional farming systems revealed that crop yields in organic systems were 20% lower than those in conventional systems, although fertilizer and energy inputs were reduced by 34 to 53%, and pesticide inputs were reduced by 97% in these organic systems (Mäder et al., 2002; Fließbach et al., 2006). In the bio-organic system, manure was slightly rotted whereas the bio-dynamic system was composted aerobically with some herbal additives and the conventional systems were either amended with stacked manure, supplemental mineral fertilizers, and chemical pesticides or exclusively fertilized with mineral fertilizers. They also reported enhanced soil fertility and higher soil microbial biomass and biodiversity in organic plots compared with other systems. The same study found mycorrhizae in the soil ameliorated plant mineral nutrition and contributed to formation of soil aggregates. For example, roots colonised by mycorrhizae in organic systems were 40% longer than those in conventional systems.

Other studies have demonstrated that organic matter (OM) is higher in conventional farming systems than in organic systems when GrM crops are used. For example, a study conducted by Temple and co-workers (1994) revealed that the supply of N by cover crops and weed management under low-input and organic farming systems were the most important challenges faced by these systems when compared to conventional farming systems in the first 4 years of the Sustainable Agriculture Farming Systems project at University of California, Davis in USA. As well, N input levels and N immobilization by soil organisms may limit N-uptake by GrM crops under organic or low-input systems than conventional systems although yields may ultimately be similar between these systems (Clark et al., 1999).

2.2.1 Green manures in organic production

For centuries, GrM crops have been used to help maintain soil organic matter (SOM) and improve soil fertility (Zentner et al., 1996). Apart from conserving and sustaining soil productivity by improving physical and biological soil conditions and preventing degradation of the soil (Milkha et al., 2001), GrM crops also serve as soil amendments and nutrient sources for subsequent crops upon mineralization (Cherr et al., 2006). Integrating legume GrM with partial fallow prevents soil erosion by wind and water and provides access to N gains from the atmosphere (Green and Biederbeck, 1995).

Many studies have reported lower or similar yield of crops that follow legume GrM crops in comparison to crops that follow tilled fallow (Zentner et al., 1996). Yields of cereals that follow deep-rooted perennial legume crops such as alfalfa are usually lower because legumes tend to use up most of the available spring soil water, leaving insufficient moisture for the subsequent crop (Brandt 1999; Zentner et al., 1996).

In recent years, the use of organic fertilizers such as GrM crops has increased considerably due to environmental awareness and the need to reduce input costs (Pappa et al., 2006). This management approach is often used by organic farmers because it is perceived to be more environmentally sound and less expensive than using inorganic mineral fertilizers (Edmeades, 2003). Using GrM crops as a substitute for commercial N fertilizer in cropping systems, enhances availability and conservation of N (Follett et al., 1991).

According to Sullivan (2003), a key benefit of growing cover crops either for GrM or for GF is N production. The amount of N produced by legume crops is dependent on the species under production, the amount of biomass produced, and the percentage of N in the plant tissues. For instance N accumulations in legume crops may range from 44.8 to 224 kg ha^{-1} of N (Sullivan, 2003). However, the amount of N produced by legumes may be affected by cultural and environmental factors such as delayed planting date, poor stand establishment, drought, and prolonged cool conditions, whereas good stand establishment, adequate soil moisture, optimum soil nutrients and pH, and good nodulation favour N production (Sullivan, 2003). Green manure legume crops are capable of contributing about 40% to 60% of their total N to the subsequent crop. For instance, a hairy vetch crop that accumulates 202 kg ha^{-1} of N before ploughing down will contribute approximately 101 kg ha^{-1} of N to the following grain or vegetable crop. However, less N is available to the second or third crop following a GrM legume, although increased yields are still evident (Sullivan, 2003).

2.2.1.1 Factors affecting the adoption of green manures

Benefits of growing annual legumes intercropped and/or in rotation with cereal grains are well documented. Annual legumes if grown in rotation with grain crops are capable of increasing grain yields and can contribute to the total N pool in the soil (Ahmad et al., 2001).

Legumes obtain N from the atmosphere by N_2-fixation in their root nodules and thus have the potential of improving yields in N-deficient soils (Ahmad et al., 2001). Legume-cereal mixtures are critical in crop rotations because they help replenish the supply of active, rapidly decomposing organic matter (Allison, 1973). Earlier reports have indicated that yield responses to previous legume crops are in the range of 50-80% more than yields in cereal-cereal rotations (Oikeh et al., 1998). Benefits of growing legumes in rotation with cereals contribute to the control of cereal diseases and insect pests, as well as improve the soil structure (Reeves et al., 1984).

The most consistent benefit of a legume crop is to increase the plant-available nitrate-N in the soil (Ahmad et al., 2001). Higher soil nitrate concentrations are due to the conservative use of nitrate by the N_2-fixing legume crop, a phenomenon called “nitrate sparing”, and the release of mineral N from legume residues. Thus, if legumes are intercropped or grown in rotation with cereal crops, it has been postulated that they can theoretically increase soil N concentration as well as reduce the decline of soil N fertility associated with intensive cereal cropping (Herridge et al., 1995).

Other benefits from GrM crops include recycling of nutrients on the farm. Nitrogen, phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S), and other minor nutrients that are accumulated during the growing season are made available to the soil when these crops are incorporated. Thus, these plant-essential nutrients are slowly released into the soil during decomposition (Sullivan, 2003). Forage legumes are also important in crop rotations because they generate income from grazing or haying while still contributing a significant amount of N to the soil from re-growth and root residues. McLeod (1982) observed that there is a high percentage of biologically fixed N in the top growth (Table 2-1).

Despite the aforementioned benefits of GrM crops such as enhanced N_2-fixation, high subsequent crop yields, and other positive effects on soil physical and chemical properties (Becker et al., 1995; Gerhardt, 1997; Shepherd et al., 2002), GrM usage is still limited in many parts of the world due to constraints such as high variability in GrM crop performance, high costs of establishment and incorporation, high prices of land and labour, lower mineral fertilizer costs, and in some cases the unavailability of appropriate seed (Becker et al., 1995)

Table 2-1 Distribution of nitrogen (as % of the total) in legume shoots and roots

Crop	Shoots	Roots
	N (%)	
Soybeans	93	7
Vetch	89	11
Cowpeas	84	16
Red clover	68	32
Alfalfa	58	42

Adapted from Sullivan, 2003.

2.2.2 Impact of green manure and green feed forage crops on soil fertility

For every tonne of grain produced, cereal grain harvest removes approximately 18 kg of N from the soil, thus re-enforcing the need to replenish soil N levels in order to sustain grain yields and protein content for long periods of time (Harris et al., 2006). Therefore, soil fertility is considered an important aspect in determining the productivity of all agro-ecosystems and it is mostly defined on the basis of the ability of a soil to supply the necessary nutrients to crops (Watson et al., 2002). Since organic farming is mainly aimed at building and maintaining soil fertility by encouraging biological processes, these systems rely heavily on organic N sources such as GrM crops (Berry et al., 2002).

In organic systems, the supply of soil mineral N comes from sources such as atmospheric deposits, manures, and mineralization from soil organic matter. However, a number of factors including soil moisture, aeration, temperature, and the nature of the organic matter will affect the amount and timing of mineralization (Berry et al., 2002). In order to ensure good rooting conditions and to optimize the production of mineralized N while minimizing greenhouse gas emissions, there is a need to effectively manage soil structure and OM (Ball et al., 2007).

Gerhardt (1997) observed that soil structure was likely to improve under long-term organic management. Additionally, Shepherd et al. (2002) noted that maintenance of soil structure was especially important in organic cropping systems. They attributed these improvements to the fact that fresh organic matter from roots and manures were added regularly to the soil, thus helping to improve soil structure.

According to SAF (2006a), there are two main sources of nutrients; i.e. from the breakdown of soil minerals and the decomposition of organic matter. Release of nutrients from organic materials begins within a few days to many years and can last for centuries, whereas release of nutrients from soil mineral breakdown is a lot slower and may take centuries for a reasonable amount of nutrient to be released, depending on the type of mineral source (SAF, 2006a).

Crop residues such as roots, chaff, stems, and leaves, which are left after crops are harvested, are the main sources of organic matter replenishment in organic farming.

Several soil properties including water infiltration, water storage, and soil particle aggregation are significantly improved by crop residues. As well, these crop residues contain nutrients such as N, P, K, S, and micro-nutrients that are vital for normal plant growth (SAF, 2006a). Organic farmers mainly depend on N from the breakdown of organic matter. In Saskatchewan soils, 17 to 56 kg ha^{-1} of plant available inorganic N is released into the soil per year from crop residue and organic matter breakdown. For example, 2000 kg ha^{-1} of wheat grain with a protein content of approximately 13 per cent will require about 64 to 78 kg ha^{-1} of N (SAF, 2006a).

In organic cropping systems, much of the N is a direct result of growing legumes that have been well inoculated with for instance, *Penicillium bilaiae* a phosphate solubilizing fungus and *Rhizobium leguminosarum biovar viciae,* a N_2-fixing bacterium, as well as GrM crops. However, the amount of N released into the soil is dependent on the type of crop and plant materials ploughed into the soil (SAF, 2006a). In green feed forage treatments, the primary pathways for N transfer from plants into soils is through decomposition of the root system and unused leaves and stems by soil micro-organisms. Since N contained in these plant materials is only released over time, it is mainly available to subsequent crops (Evers, 2006).

2.2.3 Legume-cereal intercropping in organic production

Intercropping is the simultaneous growing of two or more crops on the same piece of land during a growing season (Corre-Hellou et al., 2006; Hauggaard-Nielsen et al., 2007). By intercropping legumes with cereals, it is assumed that the legume component fixes N from the atmosphere, whereas the cereal derives its N from the soil.

Where fertilizer N is limited as in organic production, biological nitrogen fixation (BNF) is the main source of N (Fujita et al., 1992). Compared to monocropping, intercropping enhances the use of available resources, and increases yield and stability of crops (Corre-Hellou et al., 2006; Ofori and Stern, 1987; Hauggaard-Nielsen et al., 2007).

A study conducted in five European countries on monocropped pea and intercropped pea-barley concluded that pea-barley intercrops used N sources 20 to 30% more efficiently than their monoculture counterparts (Hauggaard-Nielsen et al., 2007). They noted that the relatively greater soil N uptake by barley than pea forced the pea to rely on N_2-fixation when intercropped. As well, Szumigalski and Van Acker (2006) observed greater N concentrations in wheat, canola, and weeds that were grown in association with field pea, suggesting that these non-legume crops were taking up the N that was fixed by the pea legume.

Szumigalski and Van Acker (2006) also found that on average, most intercrop treatments resulted in better land use efficiency for N than sole crops, with overall mean intercrop N yield and land equivalent ratios (NLER) values ranging between 1.10 and 1.20. The NLER simply indicates the land use advantage of a crop system (intercrop or monocrop) in terms of N yield compared to the other. For example, a NLER would show the relative area under monocropping to achieve intercropping yields under the same conditions (Szumigalski and Van Acker, 2006). Thus, a NLER greater than one in their study indicated greater land utilization efficiency for intercropping than monocropping. Their results showed that the pea-wheat-canola and pea-canola intercrops had consistently higher yield and NLER values for crop dry matter and grain yields than their monocultures.

Although many studies have reported that the fixed N is available to both current and subsequent cereal crops (Fujita et al., 1992; Pal and Shehu, 2001; Pappa et al., 2006), other studies have not observed N transfer from legume to cereal in the current year (Izaurralde et al., 1992; Ofori and Stern, 1987).

Yields and N use efficiency (NUE) of cereal crops following legume-cereal intercrops are usually better than those of cereals grown after a cereal-cereal intercrop (Fujita et al., 1992). Nair et al. (1979) observed a 30% increase in wheat yield after a maize-soybean intercrop and a 34% increase after a maize-cowpea intercrop compared to a maize-wheat rotation. Nitrogen transfer occurs through root excretion, N leached from leaves, litter fall, and dung from animals if present in the system.

2.3 Biological Nitrogen Fixation In Legume-Cereal Intercropping Systems

In simpler terms, N_2- fixation refers to biological or abiotic natural process where N in the atmosphere is converted to ammonia. Biological nitrogen fixation (BNF) happens when an enzyme called nitrogenase converts atmospheric N to ammonia

(Peoples et al., 1995). Probably the most obvious benefit of growing cereals in association with grain legumes is the increased N and grain yields per unit area compared to their monoculture counterparts (Chalk, 1998). This positive benefit for intercropped cereals is a direct result of N transfer, N-sparing (reduced competition for soil nitrate between legume and cereal components), and less nitrate immobilization during decomposition by the legume component (Chalk, 1998).

However, other studies have reported that legume monocrops produce more N than their intercrops. A study conducted in Denmark reported significant differences in shoot dry weight and N concentrations between monocropped pea and pea-barley and pea-barley-rape intercrops (Andersen et al. (2007). The monocrop pea produced the largest amount of shoot biomass and N-uptake from the middle to the end of the growing season. However, pea was not dominant in intercrops. Monocropped pea produced about 6000 kg ha^{-1} shoot dry weight compared to pea-barley and pea-barley-rape intercrops, which produced approximately 5000 kg ha^{-1} of their shoot dry weight for each combination. In another study, N accumulation in above-ground herbage was 100, 126, and 162 kg N ha^{-1} for oat, oat-lupin, and lupin, respectively (Fowler et al., 2004).

In warmer regions, especially in the tropics, legume-cereal intercropping is an old, widely adopted agricultural practice (Corre-Hellou et al., 2006; Agboola and Fayemi 1972). Intercropping legumes with non-legumes increases total grain and plant-N yields for farmers in the developing world, as it is a low-input system (Barker and Blamey, 1985). Where fertilizer N is limited, biological nitrogen fixation (BNF) is the major source of N in legume-cereal intercropping systems (Fujita et al., 1992). In developed countries, intercropping is increasingly being adopted because of more environmental awareness of soil degradation resulting from high use of chemical fertilizers (Cherr et al., 2006; Ofori and Stern, 1987), as well as a means of crop diversification (Cherr et al., 2006).

In western Canada, sustainability of cereal-cropping systems may be improved using legumes as intercrops (Ross et al., 2005). Intercropping legumes with cereals increases plant biomass and grain yield compared to their monocultures (Fujita et al., 1992). Izaurralde and co-workers (1991) reported that barley-field pea intercrops increased N yield when grown under cryoboreal sub-humid conditions.

Izaurralde and co-workers (1991) observed that on average, the proportion of N derived from air by pea intercrops was 39% higher than that derived by the single pea crop. They attributed these yield advantages by intercropping to the mutual complimentary effects of individual crops including better use of available resources such as light, water, and nutrients (Izaurralde et al., 1991).

Biological N_2-fixation in legume-cereal intercrops can be influenced by factors such as the distance between legume and cereal root systems (as N is transferred through the intermingling of the roots) crop species, plant morphology, light effect, density of intercrops, management techniques applied to crops and soils, competitive capabilities of the component crops (Fujita et al., 1992), legume plant growth, the length of the growing season, N availability in the soil, and soil types (Evers, 2006). For instance, if a legume is grown on a sandy soil with low N, it will derive most of its N from the air through N_2-fixation as opposed to a legume that is grown on a fertile river-bottom soil with plenty of available N (Evers, 2006).

2.3.1 Importance of biological nitrogen fixation in organic systems

The importance of BNF in sustainable and environmentally friendly production of food and long-term productivity of crops cannot be over emphasized. Since the inception of farming, BNF has played a key role in the provision of food and improvement of soil health (van Kessel and Hartley, 2000). Biological N_2-fixation in legumes is important because apart from its role as a source of protein N in the diet, N from legume fixation is essentially "free" N for use by the host plant and subsequent crops (Vance et al., 2000). Peterson and Russelle (1991) estimated that replacing symbiotic N with fertilizer N would cost the U.S. $7 to 10 billion annually, whereas using alfalfa as a supplier of N in rotation with corn, farmers could potentially save $200 to 300 million per year in the U.S. If farmers adopt management practices that make use of the more economically viable and environmentally prudent N fixation, agriculture and the environment will benefit (Peoples et al., 1995).

Furthermore, N fixed by legume crops is directly incorporated into organic matter and thus is not as susceptible to volatilization, denitrification, and leaching compared to fertilizer N. This poses much less risk of potential contamination resulting from N losses to the environment (Vance et al., 2000). While there is affordability and accessibility of N fertilizer by farmers in the developed world, the opposite is the case for most of the farmers in the developing world. Poor infrastructure and transportation, and higher input costs are some of the main constraints for the unavailability of fertilizer N to subsistence farmers. This leaves legumes as the only source of N. In order to ensure future sustainability of N, there is need to have germplasm with enhanced N acquisition and use, improved crop management techniques to efficiently use applied N fertilizer, as well as renewable N resources (Vance, 2000).

2.3.2 Measurement of biological nitrogen nixation by the ^{15}N natural abundance method

Precision in estimating BNF is largely dependent on the method of measurement used (Ledgard and Steele, 1992). The natural abundance method was reviewed by Shearer and Kohl (1986) and is essentially the same as the ^{15}N-isotope dilution method except that ^{15}N-labelled material is not added.

The ^{15}N-isotope dilution method is calculated by using differences in ^{15}N enrichment of atmospheric N and soil N. The ^{15}N natural abundance method utilizes the small, natural enrichment of ^{15}N present in the soil, which is assumed to be relatively uniform over time and with soil depth. This method is not affected by requiring the legume and reference crop to have similar N uptake characteristics, as is the case with the ^{15}N-isotope dilution method (Ledgard and Steele, 1992; Bremer and van Kessel, 1990).

Nitrogen in the atmosphere has a percent atom ^{15}N of 0.3663 (Mariotti, 1983). The value 0.3663 equates to a $\delta^{15}N$ value of 0 or a ^{15}N atom excess in relation to atmospheric N of 0 whereas $\delta^{15}N$ values in soil N range from -6 to 16 (Shearer and Kohl, 1986). However, $\delta^{15}N$ values in most soils are positive because of discrimination between the ^{14}N, a lighter isotope and ^{15}N, a heavier isotope, as a result of biological, physical, and chemical processes (Shearer et al., 1974).

As well, there are differences in $\delta^{15}N$ between N_2-fixing and non-N_2-fixing crops. When clover (*Trifolium* spp.), soybean (*Glycine max* L. Merr.), and grass were analysed for $\delta^{15}N$, N_2-fixing species had lower $\delta^{15}N$ values than the grass species (a reference crop) or the soil in which these species were grown (Delwiche and Stein, 1970). They concluded that the differences in the $\delta^{15}N$ values between the legumes and grass could be used to estimate the N fixed by the legume crop.

The main challenge faced by the $\delta^{15}N$ method to estimate N_2-fixation is the spatial and temporal variability in the $\delta^{15}N$ of N available in the soil and the small difference between the soil $\delta^{15}N$ and N in the atmosphere (Bremer and van Kessel, 1990). However, these problems have been overcome by modern and precise stable isotope ratio mass spectrometers that are equipped with dual or triple collectors that can detect even the smallest of differences of atomic % ^{15}N values (Bremer and van Kessel, 1990).

2.4 Green Manure and Green Feed Forage Crops in this Study

Short-rotation forage crops serve as both cover crops when they occupy land meant for pasture or for hay and function as green manures when they are finally incorporated into the soil or killed in the case of no-till management (Sullivan 2003). There is a rapid population increase of micro-organisms in the soil following ploughing down of the GrM crop (Sullivan, 2003). These help to break down and decompose the dead plant and animal materials, thus making nutrients available through mineralization that were previously held (immobilized) in the plants and micro and macro fauna to the succeeding cereal crops (Sullivan, 2003).

A major benefit for green manuring is the addition of OM to the soil. When micro-organisms break down the OM, compounds resistant to decomposition, such as gums, waxes, and resins contribute to the SOM (Sullivan, 2003). These compounds together with mycelia, mucus, and slime produced by the soil microbial biomass help bind together soil particles as granules, or soil aggregates. Thus, well-aggregated soils till easily, are well aerated, and have high water infiltration rates (Sullivan, 2003). High levels of organic matter also influence soil humus, which is the end product of plant and animal material decay in the soil (Sullivan, 2003).

However, some studies have refuted claims that GrM add significant amounts of OM and microbial biomass pools to the soil, suggesting that the benefits of GrM crops to the soil depend on the environment, management, and biomass accumulation of the GrM crops (Cherr et al., 2006). As well, the contribution of GrM residues to the soil may be minimal annually compared to already existing OM pools in the soil. A short-term study revealed that 15 % of red clover N applied to maize (*Zea mays* L.) was taken up, whereas

19 and 28 % of N was recovered in microbial biomass and soil organic fractions (N'Dayegamiye and Tran, 2001).

2.4.1 Field pea (*Pisum sativum* L.)

Apart from being grown for sale as a cash crop either dry, fresh, frozen, or canned for human consumption (Oelke et al., 1991), field pea may also be grown as a green manure or green fallow crop (McKay et al., 2003). Green manuring and green fallowing are beneficial to current and subsequent soil and crop productivity. The benefits of using field pea as a green fallow (when field pea is grown during a period not intended for production) include protecting soil from erosion and improving soil quality (McKay et al., 2003), compared to black fallow (bare land). As a legume, field pea is important for fixing N into the plant from the atmosphere in a symbiotic association with rhizobia. Thus, field pea, if cultivated as a GrM, is beneficial to the current cereal crop if intercropped, due to N-sparing where field pea would fix N from the atmosphere, thus sparing soil N for the cereal component. When ploughed down as a GrM, the field pea adds nutrients to the soil for the following crop (Cherr et al., 2006).

2.4.2 Oats (Avena sativa L.)

Historically, oat was grown to feed horses and livestock on farms. However, the development of fossil fuel powered machinery in agriculture has replaced the need for draft horses. As well, oat has been replaced with higher energy alternatives such as barley and silage, thus drastically reducing the feed demand for oat. Although in the past several years the overall acreage and production of oat has been falling with Alberta and Manitoba producing well below the 1960's production (AAFRD, 2005), recently with a greater portion of this crop being exported abroad for both human and racehorse consumption, demand for high quality oat has since increased and this has led to an increase in oat production on the prairies (May et al., 2004).

In western Canada, oat was traditionally the last crop to be seeded on farms, yet still harvested or used as fodder depending upon needs. The late seeding of this crop allowed for the opportunity to control wild oat (*Avena fatua* L.) with tillage before planting. Oat was usually harvested and consumed locally with less attention paid to quality. However, recently According to AAFC (2006 a), oat is grown on approximately

1 to 1.2 million hectares in western Canada. This crop has been cited as very useful in crop rotations and is easily marketed for feed or milling purposes. High quality oat, with high productivity or yield, requires varieties well adapted to areas of production. Oat is widely used as a forage crop or green manure crop on the prairies (SAF, 2004 b). Its vigorous root system, rich fibre content, and large biomass make it desirable in a forage mix annual cropping system. Moreover, it is easily cultivated, has rapid development, and high dry matter and grain yield if properly managed (Arelovich et al., 1996). Oat is cultivated for grain, as a protein source, for hay, as a winter cover, and as a forage crop in the growing or 'milk' stage (SAF, 2004 b).

2.4.3 Triticale (*Triticale* Wittmack cv. Pika)

In this study, triticale was chosen as a cereal because of its perceived allelopathic properties of suppressing weeds (Khanh et al., 2005). For instance, in their study, Khanh et al. (2005) observed that allelopathic crops, when used as cover crops, mulch, smother crop, green manure, or grown in rotational sequences, were helpful in reducing noxious weeds and plant pathogens and improved soil quality and crop yield.

According to FAO (2004), triticale is a 'human-made' cereal crop that was developed by crossing wheat (*Triticum* sp. L) and rye (*Secale cereale* L.) and is well adapted to harsh, low-input sustainable production systems. Despite the original intention for developing triticale being for human consumption (as it has a high nutritional content), it has not been a major cereal crop. However, triticale use as a grazing crop to supplement native grass pasture, as a silage and conserved hay crop, and as a GrM is steadily increasing. In most countries, triticale is used as an important source of fodder and its use for grazing, forage, silage, hay, and multi-purpose crop have seen considerable increase (FAO, 2004).

One of the useful qualities of triticale in agricultural production systems may be its allelopathic potential to suppress weeds. A study conducted by Dhima et al. (2006) revealed that triticale used as a cover crop significantly reduced the emergence and growth of barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], and bristly foxtail [*Setaria verticillata* (L.) P.Beauv.]

Triticale is still considered suitable for human consumption owing to its high levels of lysine and energy. In Canada, triticale is often used as a minor component in multi-grain breads and the overall market for this crop for human diets still remains small (AAFC, 2006a). Although the area seeded to triticale as a grain crop remains limited in western Canada, it has some use in intercropping, pastures, and crop rotation. Triticale possesses superior quality and high grain yield potential for swine feed and may be beneficial for the poultry industry. The main advantage with spring triticale over other spring cereals is its drought tolerance. As well, spring triticale yields better than other spring forage crops such as barley and oat. For instance, triticale can yield as much as 10% higher than barley or oats and under dry land conditions, this difference can be critical to livestock producers (AAFC, 2006a).

For winter triticale, the main advantage is seen in its extension of early spring and late fall grazing (SAF, 2004b). Triticale has been described as better in grain yield and better adapted to stress conditions than other cereals. Using triticale for silage, followed by grazing, and as an under-seeding crop to fall triticale or to spring barley are seen as valuable and sustainable cropping applications of this crop (SAF, 2004b).

Despite, its limited use in North America, the area seeded to triticale may increase significantly in the near future as the demand for ethanol-based fuel continues to increase in this part of the world. Canadian studies suggest that spring and winter triticale varieties are both suitable for the conversion process into ethanol, thus offering potential high crop yields and lower prices as compared to wheat. With most automobile manufacturers moving toward designing engines that can take in as much as 85% ethanol in the fuel (E85 standard) in the United States and Canada, there could be a huge domestic demand for crops like triticale, oats, wheat, barley, and other cereals for ethanol production (AAFC, 2006a).

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3 PRODUCTIVITY OF GREEN MANURE AND GREEN FEED FORAGE OPTIONS

3.1 Introduction

Some of the main forces behind the growth of organic agriculture include reduced input costs and diversification of market opportunities. One of the challenges of producing crops organically is maintaining adequate soil fertility, including nitrogen (N). Nitrogen is one of the major nutrients needed for crop growth and development and is required for several functions within the plant. Nitrogen is used in the production of high quality protein-rich food and is a key component of amino acids, which are used to assemble proteins and nucleic acids (Havlin et al., 1999).

Crops that are incorporated into the soil while they are still green are referred to as green manure (GrM) crops or cover crops. Organic cropping systems rely on the inclusion of GrM crops in their rotations to supply the much needed N in the soil. A GrM crop not only supplies N, but helps retain the N in the soil ensuring that the added N is used by current and subsequent crops (Fowler et al., 2004). Since organic production does not permit the use of soluble inorganic N fertilizers, crop rotations that optimise N_2-fixation and retention of soil N are one of the main ways of managing N supply to crops (Watson et al., 2002).

There has been a general decline in soil organic matter (SOM) concentrations and mineralizable N reserves over time on the Canadian prairies and the Northern Great Plains of the United States under conventional management (Biederbeck et al., 1993). In order to optimize crop production, one of the key factors to consider in organic farming is the improvement of soil fertility through management of SOM (Watson et al., 2002).

Over the past decade, interest in GrM crops has revived due to the role they play in improving soil fertility by adding biomass as organic matter in crop rotations (Jannink et al., 1996). Green manures also improve soil tilth, soil aggregate stability, and if legumes, contribute N fixed from the atmosphere (SAF, 2006).

Intercropping legumes with cereals has the potential to address N supply in organic cropping systems. Although some studies have provided evidence that the legume provides N both to the current and subsequent cereal crops (Pal and Shehu, 2001; Pappa et al., 2006), other studies have shown no evidence for transfer of N from legume to the cereal in the growing year (Ofori and Stern, 1987; Izaurralde et al., 1991). Contradictory results suggest that N transfer happens under certain conditions depending on factors such as soil temperature, moisture content, and available soil N.

According to Corre-Hellou and co-workers (2006), intercropping legumes with cereals is thought to stimulate competition for soil N; the intensity of competition is dependent on the supply of soil N and the plant densities (Corre-Hellou et al., 2006). Other studies also have reported that BNF in legume-cereal intercrops can be influenced by several factors including density of intercrops and competitive capabilities of the component crops (Fujita et al., 1992), legume plant growth, the length of the growing season, N availability in the soil, and soil type (Evers, 2006). Although there are benefits of growing GrM crops either alone or as intercrops in terms of long-term sustainability by adding nutrients to the soil and better yields of subsequent crops, farmers face a loss of income in the plough-down year. Legume and cereal cover crops that are grown alone or intercropped and harvested for above-ground biomass while still green are called green feed forages (GF). One alternative to GrM may be to grow crops as GF, so farmers can harvest these crops as forage for their animals or sell to other livestock producers, yet still benefit from the added N from BNF.

Removal of plant material as GF may pose its own challenges such as depleting soil nutrients for the next crop. However, if GF crops are harvested early there is potential to limit the removal of nutrients, particularly as compared to nutrient removal by annual grain crops. Currently, there are no studies that have evaluated the productivity of different GrM versus GF options in organic cropping systems. This study involved growing field pea and cereal crops, alone or in combination, and managing them as either GrM or GF to investigate the overall productivity of these management systems.

We hypothesized that; (i) the GrM and GF management systems would produce similar above-ground biomass and have similar N accumulation; (ii) increasing cereal density in a legume-cereal intercrop would increase the amount of N_2-fixation by the legume component. Specific objectives of this part of the study were to: i) compare biomass and N yield in GrM and GF management systems;

ii) investigate whether increasing cereal density enhances N_2-fixation in the intercropped legume; iii) evaluate soil N levels following GrM and GF treatments; and iv) observe whether monocropped or intercropped triticale would suppress weeds through its allellopathic properties

3.2 Materials and Methods

3.2.1 Study sites

The study was conducted at two sites in Saskatchewan, Canada. The first site was established in 2004 at Vonda, SK on a commercial organic farm. The site had been seeded to wheat in 2003. The Vonda site is situated at 52˚19′02.28″ N and 106˚04′59.47″ W (Legal location NE 33-38-1 W3) on a gently sloping and dissected terrain with slopes ranging from 0.5 to 2% (Acton and Ellis, 1978). The soil was a very fine sandy loam Orthic Black Chernozem of the Blaine Lake Association. Soils are moderately calcareous, silty glacio-lacustrine deposits (Acton and Ellis, 1978).

The second site was established at Delisle, SK in 2005 on a commercial organic farm. The site was seeded to wheat in 2004. The Delisle site was located at 51˚58′49.90″ N and 107˚01′52.03″ W (Legal location NE 12-35-8 W3). The soils belong to the Bradwell Association and are predominantly Orthic Dark Brown Chernozems and are sandy loam to loam (Ellis et al., 1970). Soils are moderately calcareous, sandy glacio-lacustrine deposits having over 15% clay. The terrain sits on glacio-lacustrine plains of very gently undulating slope (0.5 to 2%) described as ridge and swale with limited drainage (Ellis et al., 1970).

3.2.2 Experimental procedure

The study consisted of a two-year rotation at each study site with the first cycle (treatment year) established at Vonda in 2004 and a second cycle (wheat year) following in 2005. At Delisle, the first cycle was started in 2005 and a second cycle followed in 2006. In the first cycle, the experiment consisted of 16 treatments, in which field pea (*Pisum sativum* cv 40-10 silage pea), oat (*Avena sativa* L. cv AC Morgan) and triticale (X *Triticosecale* Wittmack cv Pika) were grown alone or in combination, and managed as either GrM or GF. Intercropped oat was seeded at three t target densities of 50, 100, and 150 plants m^{-2}. Wheat (*Triticum aestivum* L. cv AC Barrie) and tilled fallow served as cropped and uncropped controls, respectively (Table 3-1). In the second year, all plots were seeded with wheat (*Triticum aestivum* L. cv AC Elsa). Treatments at both sites were arranged in a randomized complete block design with four replicates.

3.2.2.1 First year activities

In the spring, composite soil samples were collected prior to seeding and tillage at depths of 0 to 15, 15 to 30, and 30 to 45 cm using a Dutch auger (6 cm diameter x 15 cm depth). Ten random points across each site were sampled. The ten samples from a specific depth were combined, mixed and a sub-sample placed in a plastic bag. These samples were sent to ALS Laboratories (Saskatoon, SK) for initial characterization of the physical and chemical characteristics of the soil including pH (Hendershort et al., 1993), and electrical conductivity (EC) (Janzen, 1993). Both methods used a 1:2 soil:water extraction. Plant available NO_3^- and NH_4^+ were extracted with 2.0 *M* KCl and analysed using a Technicon auto-analyser (Maynard and Kalra, 1993) (Table 3-2).

Pre-seeding tillage was accomplished using a tandem disc to incorporate previous crop residues and to control early emerging weeds. Seeding was accomplished using a small-plot air seeder at an approximate depth of 5 cm. Treatment plots measured 4 m by 6 m and were seeded with 0.2 m row spacing. At Vonda, treatment plots were seeded on May 11, 2004 and at Delisle, plots were seeded on May 20, 2005.

3.2.2.2 Seeding rates

Seeding rates were 157 kg ha^{-1} for monocropped field pea (FP_{mono}), 88 kg ha^{-1} for monocropped oat (O_{mono}), and 94 kg ha^{-1} for monocropped triticale (TR_{mono}). These seeding rates provided target populations of 95 plants m^{-2} FP_{mono} and 250 plants m^{-2} for O_{mono}, and TR_{mono}. For the intercrop treatments, field pea was seeded at 100 kg ha^{-1}along with oat at rates of 18, 35 and 54 kg ha^{-1}(FP+O1, FP+O2, and FP+O3, respectively). The intercrop field pea seeding rate represented approximately 60% of the monocropped rate. The highest rate of oat represented approximately 60% of the monocropped oat rate. The pea-triticale intercrop treatment (FP+TR) was seeded to 100 kg ha^{-1} field pea and 54 kg ha^{-1} triticale. The target plant densities for intercrops were 60 plants m^{-2} field pea; 50, 100, and 150 plants m^{-2} oat; and 150 plants m^{-2} triticale, respectively.

Table 3-1 Green manure (GrM) and green feed forage (GF) treatments at Vonda (2004) and Delisle (2005)

Treatment	**Seeding Rates**		**GrM**	**GF**	**Control**
	Plants m^{-2}				
	Pea	**Cereal**			
Control-SF†	-	-			X
Control-Wh‡	-	250			X
Field pea monocropped (FP_{mono})	95		X	X	
Field pea + Oat 1 (FP+O1)§	60	50	X	X	
Field pea + Oat 2 (FP+O2)§	60	100	X	X	
Field pea + Oat 3 (FP+O3) §	60	150	X	X	
Oat monocropped (O_{mono})		250	X	X	
Field pea + Triticale (FP+TR)	60	150	X	X	
Triticale monocropped (TR_{mono})		250	X	X	

† = Tilled fallow-control
‡ = Wheat-control
§ = Field pea + Oat 1, 2, & 3 = 50, 100, & 150 plants m^{-2} respectively

Table 3-2 Physical and chemical characterization of soil at Vonda in 2004 and at Delisle in 2005 prior to seeding the treatment crops

Site-Year	**Depth**	**Texture**	**BD†**	**NO_3-N**	**P**	**K**	**SO_4-S**	**pH**	**EC**
	(cm)		(g cm^{-3})	———————kg ha^{-1}———————					(mS cm^{-1})
Vonda-2004	0-30	Clay loam	1.15	26	20	1114	46	7.8	0.3
	30-60	Clay loam	ND	9	7	411	>96	7.9	1
Delisle-2005	0-15	Loam	ND	28	27	> 672	29	7.2	0.3
	15-30	Loam	ND	29	ND	ND	>54	8.1	0.4
	30-45	Clay loam	ND	47	ND	ND	>96	8.1	1.8

ND = Not determined

Wheat was seeded at a rate of 90 kg ha^{-1} to provide a target density of 250 plants m^{-2} (Table 3-1). In order to efficiently test the hypotheses in this study, comparisons were made by comparing the four management systems and not individual treatments within these systems.

Field pea seed was inoculated with Tagteam (Novozyme Biologicals, Saskatoon, SK. 2005) immediately prior to seeding. The peat-based inoculant contains *Penicillium bilaiae* a phosphate solubilizing fungus and *Rhizobium leguminosarum biovar viciae,* a N_2-fixing bacterium. Inoculant was applied according to the manufacturer's recommendations, equivalent to 2.2 kg inoculum per 1360 kg of seed.

3.2.2.3 Plant sampling, GrM plough-down, and GF harvesting

Sampling, fallow tillage, plough-down, and harvest dates are reported in **Table 3-3**. The tillage fallow-control plots were tilled twice to control weeds. Prior to incorporating the GrM plants, shoots were collected from each treatment plot. Five strips, each 1 m long were randomly selected and harvested representing a total area in each plot equivalent to 1 m2 (i.e., row spacing of 0.2 m). Shoots were cut approximately 5 cm above the ground using hand sickles. Samples were oven-dried for 72 h at 60oC and weighed. These samples were ground and sub-samples were collected for plant tissue analyses (total N) using a LECO CNS 2000 (LECO Corporation, St. Joseph, MI, USA) analyser.

The two crops in the intercrop samples were separated while fresh and dried separately only at Delisle. At Vonda, intercropped samples were not separated as the decision to separate samples was only made after samples had been collected and processed. The C:N ratios were determined only for Delisle. Green manure treatments were ploughed down when the field pea was at full bloom using a small-plot tractor equipped with a tandem disk (Figure 3-1).

Green feed forage plots were harvested when at least 50% of the oat was in the dough stage of development (SAF, 2004b). Pods on the field pea were still green. Five 1-m strips were selected within each plot and hand harvested with sickles approximately 5 cm above ground. Samples were oven dried at 60oC for 72 h, weighed, ground, and sub-samples collected for plant tissue N analysis. The remaining GF material was swathed and plant materials removed from the plots.

Table 3-3 Seeding, plough-down and sampling dates at Vonda and Delisle in the treatment year

Site	Date	DAP†	Activity
Vonda	12 May 2004	0	Seeded all plots
	11 June 2004	30	1st tillage (fallow plots)
	16 July 2004	46	GrM sampling
	17 July 2004	47	2nd tillage (fallow plots)
	18 July 2004	48	GrM plough-down
	29 July 2004	59	GF sampling
	31 July 2004	61	GF harvest
	26 August 2004	87	Wheat-control sampling
	15 September 2004	107	Wheat-control harvest
Delisle	20 May 2005	0	Seeded all plots
	18 June 2005	29	1st tillage (fallow plots)
	11 July 2005	52	GrM sampling
	13 July 2005	54	GrM plough-down
	17 July 2005	58	2nd tillage (fallow plots)
	21 July 2005	62	GF sampling
	23 July 2005	64	GF harvest
	30 August 2005	104	Wheat-control sampling
	9 September 2005	114	Wheat-control harvest

† = Days after planting.

Figure 3-1 Small tractor equipped with a tandem disk incorporating green manure treatments nine weeks after seeding when the field pea was at full bloom at Vonda

Wheat-control plots were sampled for biomass and N analysis. As described above, five 1-m strips were hand harvested with sickles approximately 5 cm above ground. Samples were oven dried at 60°C for 72 h, ground, weighed, and sub-samples collected for plant tissue N analysis.

In order to determine %Ndfa, sub-samples from the GrM and GF treatments were pulverized to a fine powder in a ball-mill and weighed (1.00±0.05 mg) for natural ^{15}N abundance determination. The ^{15}N analyses were accomplished using a Europa Tracer 20-20 Isotope Ratio mass spectrometer (Europa Scientific, Crewe, UK) interfaced with an ANCA-GSL elemental analyser (Sercon Ltd., Cheshire, UK). Natural ^{15}N abundance was calculated according to (Bremer and van Kessel 1990):

$\delta\ ^{15}N = [\text{atom}\ \%\ ^{15}N_{(sample)} - \text{atom}\ \%\ ^{15}N_{(standard)}/\text{atom}\ \%^{15}N_{(standard)}]1000$ [3.1];

where the standard is atmospheric N (0.3667 atom % ^{15}N).

The % Ndfa was calculated as follows:

$\%\ Ndfa = [(x - y)/(x - c)]\ 100$ [3.2];

where x = $\delta\ ^{15}N$ of the non-N_2 fixing reference plant; y = $\delta\ ^{15}N$ of the N_2-fixing crop; c = $\delta\ ^{15}N$ of field pea grown in an N-free medium. The c value used in this study for field pea was 0.7 (Bremer and van Kessel 1990). Monoculture oat was selected as the non-N_2 fixing reference crop.

3.2.2.4 Statistical analyses

Data were statistically analysed using SPSS 14.0 for windows (SPSS 14.0, 2005). A one-way analysis of variance (ANOVA) was used to analyse individual treatments. Group treatments were compared using orthogonal contrasts. Contrasts were used in this study in order to test the research hypotheses because contrasts give a focus test of means. The ANOVA assumptions were assessed prior to conducting the ANOVA tests.

In this study, orthogonal contrasts were developed to assess system differences. Specifically, the systems compared included: GrM versus GF, GrM versus Control-SF, GrM versus Control-Wh, GF versus Control-SF, GF versus Control-Wh, GrM intercrops versus GF intercrops. Field pea was evaluated for differences within the GrM and GF systems.

Homogeneity of variance was assessed using the Levene's statistic ($P \leq 0.05$) to assess the equality of variances among different treatments. The data were assessed for normality using the Kruskall-Wallis test ($P \leq 0.05$). The generated ANOVA table gave details of sum of squares (*SS*), degrees of freedom (*df*) for error, mean squares (*MS*) for error values, and the F-distribution value, of between groups and within groups.

The Least significant differences (*LSD*) were determined by using pair-wise comparison of group means i.e., mean squares (*MS*) error within groups and degrees of freedom for error within groups from the ANOVA tables. It is important to note that *LSD* values in this study were calculated from the contrasts comparing the systems and not individual treatments within systems. The following equation was used to calculate *LSD* values in this study:

$$LSD_{0.05} = t_{0.05}\sqrt{2MS/n} \qquad [3.3];$$

where t = tabular t value for degrees of freedom for error, *MS* = mean squares for error within groups, n = number of treatment replicates.

In calculating the *LSD*, the *t*-test statistic was used to test the hypotheses in this study whether there were real differences between systems or whether the differences were by chance. In this case the null hypothesis, which is assumed to be true until proven wrong, was that there were no differences between systems. Therefore, the *t*-test basically was used to compare actual differences between two means in relation to the variation in the data, which was expressed as the standard deviation of the difference between the means.

3.3 Results

3.3.1 Weather data at Vonda and Delisle

The total rainfall recorded in 2004 at Vonda was 41 mm less than the total recorded for 2005 at Delisle, whereas the average rainfall in 2004 was 10 mm less than the average rainfall recorded in 2005 (Table 3-4). However, in both years, the total rainfall was comparable to the 30 year average. In both years, the month of June recorded more rainfall than other months. However, mean daily temperatures from May to August were similar for the two years as well as the 30 year average temperatures with the month of July being the warmest.

Table 3-4 Climatic data for Saskatoon and adjacent areas as recorded at the Saskatoon international airport for Vonda in 2004 and Delisle in 2005

Precipitation (mm)			
Month	**30 year average†**	**2004** Vonda	**2005** Delisle
May	20	27	28
June	44	80	161
July	63	75	54
August	58	74	54
Average	46	64	74
Total	**185**	**256**	**297**

Mean daily temperature (^{0}C)			
	30 year average†	**2004** Vonda	**2005** Delisle
May	11.5	8.5	10.0
June	16.0	13.5	14.5
July	18.2	17.5	17.5
August	17.3	14.5	15.5

† = Based on Saskatoon weather data from 1971-2000 from Environmental Canada

3.3.2 Above-ground dry matter production at Vonda and Delisle

At both sites, the GF system produced more than twice the amount of biomass and accumulated twice as much N as the GrM system except for the TR_{mono} (Table 3-5 and Table 3-6). Since the GF treatments were sampled approximately two weeks later than the GrM treatments, the above-ground biomass and N accumulation in all the GF treatments were consistently higher than the GrM treatments. Whereas FP_{mono} treatments produced the highest amount of biomass in the GF system, FP_{mono} did not produce higher amounts of biomass in the GrM system.

Compared to the Control-Wh system, the GrM system produced significantly less biomass. All the GrM intercrops produced similar amounts of biomass and accumulated similar amounts of N. Similarly, the intercrops in the GF management system produced similar amounts of biomass. The FP_{mono} under the GF regime produced the highest biomass followed by the intercropped treatments, i.e., FP+O1, FP+O2, FP+O3, and FP+ TR (Table 3-5). When the GF system was compared with the Control-Wh system, the GF produced significantly higher biomass. Thus, the Control-Wh treatments produced biomass intermediate between GrM and GF management systems. Triticale treatments had the lowest biomass in both management systems. However, monocropped triticale treatments under GrM and GF systems had similar biomass (Table 3-5).

At Delisle, biomass was significantly higher in the GF treatments than the GrM system (Table 3-6). Similarly, the GF intercrops produced more biomass than the GrM intercrops. However, there were no differences observed between the GrM system and the Control-Wh system. When the GF system was compared with the Control-Wh system, the GrM regime produced significantly higher biomass than the Control-Wh system. When the GrM FP+O3 and the GF FP+O3 were compared individually, they produced similar amounts of biomass. As well, the GrM FP+TR produced similar biomass to the GF FP+TR treatment (Table 3-6). Ranking of the treatments at this site was similar to that observed at the Vonda site, where GF treatments were consistently higher than those treatments under the GrM management.

Table 3-5 Biomass, N accumulation and %N for green manure (GrM), green feed forage (GF), and wheat-control plots in the treatment year at Vonda in 2004. The GF system was sampled approximately 14d after GrM system.

Vonda Treatments in 2004		
Treatment ID	**Mean Biomass**	**N accumulation**
Control	**kg ha^{-1}**	
Control-SF[†]	NA	NA
Control-Wh[‡]	3111	31
GrM		
Field pea monocropped (FP_{mono})	2042	65
Field pea + Oat 1 (FP+O1)[§]	2090	54
Field pea + Oat 2 (FP+O2)[§]	2066	48
Field pea + Oat 3 (FP+O3)[§]	2353	44
Oat monocropped (O_{mono})	2086	26
Field pea + Triticale (FP+TR)	1494	47
Triticale monocropped (TR_{mono})	688	15
GF		
Field pea monocropped (FP_{mono})	6095	161
Field pea + Oat 1 (FP+O1)[§]	4288	93
Field pea + Oat 2 (FP+O2)[§]	5212	99
Field pea + Oat 3 (FP+O3)[§]	4759	82
Oat monocropped (O_{mono})	3367	24
Field pea + Triticale (FP+TR)	4060	85
Triticale monocropped (TR_{mono})	719	11
$LSD_{0.05}$	**1147**	**38**
Orthogonal contrasts		
GrM vs GF	< 0.01*	< 0.01*
GrM vs Control-Wh	< 0.01*	0.35
GF vs Control-Wh	0.01*	< 0.01*
GrM intercrops vs GF intercrops	< 0.01*	< 0.01*

* = Significant at $P < 0.05$ level
† = Tilled fallow-control
‡ = Wheat-control
§ = Field pea + Oat 1, 2, 3 = 50, 100, and 150 m^{-2}, respectively

Table 3-6 Biomass, N accumulation and C:N ratios for green manure (GrM), green feed forage (GF), and wheat-control plots in the treatment year at Delisle in 2005. The GF system was sampled 14d after GrM system.

	Delisle Treatments in 2005					
Treatment ID	**Mean Biomass**	**N accumulation**	**C:N Ratio (Straw)**		**%N**	
Control	**kg ha^{-1}**		**Pulse**	**Cereal**	**Pulse**	**Cereal**
Control-SF†	-	-	-	-	-	-
Control-Wh‡	3600	51	-	28	-	1
GrM						
Field pea monocropped (FP_{mono})	2543	82	13	-	3	-
Field pea + Oat 1 (FP+O1)§	2958	13	13	19	3	2
Field pea + Oat 2 (FP+O2)§	3630	11	11	19	4	2
Field pea + Oat 3 (FP+O3)§	3358	13	13	23	3	2
Oat monocropped (O_{mono})	4238	73	-	23	-	2
Field pea + Triticale (FP+TR)	1865	67	11	11	3	4
Triticale monocropped (TR_{mono})	1358	45	-	12	-	3
GF						
Field pea monocropped (FP_{mono})	5210	145	15	-	3	-
Field pea + Oat 1 (FP+O1)§	3660	123	15	23	2	2
Field pea + Oat 2 (FP+O2)§	4733	189	13	23	3	2
Field pea + Oat 3 (FP+O3)§	3380	149	13	27	3	2
Oat monocropped (O_{mono})	5758	84	-	28	-	1
Field pea + Triticale (FP+TR)	3010	101	16	12	3	3
Triticale monocropped (TR_{mono})	1770	48	-	15	-	3
$LSD_{0.05}$	**1685**	**46**	-	-	-	-
Orthogonal contracts	***p-value***		-	-	-	-
GrM vs GF	$< 0.01^*$	$< 0.01^*$	-	-	-	-
GrM vs Control-Wh	0.06	$< 0.01^*$	-	-	-	-
GF vs Control-Wh	$< 0.01^*$	0.01^*	-	-	-	-
GrM intercrops vs GF intercrops	$< 0.01^*$	0.01^*	-	-	-	-

* = Significant at $P < 0.05$ level
† = Tilled fallow-control
‡ = Wheat-control
§ = Field pea + Oat 1, 2, 3 = 50, 100, and 150 m^{-2}, respectively

Whereas the GF FP_{mono} treatment accumulated the highest biomass at the Vonda site, O_{mono} had the highest biomass at Delisle. Furthermore, all cereal crops, at Delisle regardless of the management system, produced considerably more biomass than cereal crops at Vonda. When the GF system was compared with the Control-Wh system, the GF system had significantly more biomass than the Control-Wh system. Furthermore, all GF intercrops had significantly higher biomass than their GrM counterparts.

3.3.3 Plant nitrogen accumulation

At Vonda, GF crops accumulated consistently more N than crops in the GrM system ($P < 0.05$) except for O_{mono} and TR_{mono}, which were similar in both regimes (Table 3-5). However, it should be noted that the GF system was sampled two weeks later than the GrM system. Under GF management, FP_{mono} accumulated more N compared to the GrM FP_{mono}. The GF FP_{mono} was followed by the four GF intercropped treatments, FP+O1, FP+O2, FP+O3, and FP+TR (Table 3-5), all of which accumulated similar amounts of N. Green manure treatments followed a similar trend to that exhibited by the GF treatments, with the FP_{mono} accumulating the highest amount of N followed by the four intercrops, FP+O1, FP+O2, FP+O3, and FP+TR, which had similar N amounts.

Whereas the GrM O_{mono} treatment had similar biomass yield to FP_{mono} (Table 3-5), its N accumulation was comparatively lower than that of FP_{mono} or the intercrops. However, under the GF system, O_{mono} had significantly less biomass and N accumulation than FP_{mono}. Triticale accumulated the least amount of N in the GrM and GF systems reflective of its slow growth. The Control-Wh system accumulated similar amounts of N to the GrM system. However, the GF system accumulated significant amounts of N compared to the Control-Wh system (Table 3-5).

At Delisle, treatments under GF management accumulated more N than those under GrM management and the Control-Wh treatment (Table 3-6). The GF FP+O2, FP+O3, and FP_{mono} (which had similar N amounts) accumulated higher levels of N than all other treatments. All monoculture cereals accumulated relatively lower levels of total N. However, among monoculture cereals, oat accumulated more N under both the GrM and GF systems followed by the Control-Wh system. The TR_{mono} treatment accumulated the least amount of N under both GrM and GF regimes. When the GrM and Control-Wh systems were compared for N accumulation, the Control-Wh accumulated significant amounts of N than the GrM system. The GF intercrops accumulated significant amounts of N compared to their GrM counterparts.

Monocropped wheat and oat had higher C:N ratios whereas the TR_{mono} had a lower C:N ratio (Table 3-6). Monoculture FP had a comparatively lower C:N ratio, whereas all intercrops except for the FP+TR treatment had a lower C:N ratio for the pulse component and a higher C:N ratio for the cereal component.

3.3.4 Nitrogen fixation (Ndfa) at Delisle

Nitrogen fixation was measured only at Delisle in 2005. Green forage treatments obtained significantly higher ($P < 0.05$) amounts of N through BNF compared to their GrM counterparts. As well, all GF intercrops derived significant amounts of N from the atmosphere than their GrM counterparts (Table 3-7).

The GF FP+TR treatment derived a lower amount of N from BNF than the GF FP+O2 (Table 3-7). Other GrM intercrops and the FP_{mono} fixed similar amounts of N (i.e., there were no significant differences in Ndfa in all GrM treatments). There were no significant differences in BNF between FP_{mono} versus its intercropped counterparts under either regime.

The GF FPmono, FP+O1, FP+O2, and FP+O3 all fixed similar amounts of N through BNF. Under both the GrM and GF management system, there were no significant differences between the FP+O3 and FP+TR in their respective systems (FP+O3 and FP+TR had the same cereal density in both systems).

When N from Ndfa was considered as a percent of total N, the GF system recorded significantly higher N percentages than the GrM system. Under the GrM system, all treatments had similar N percentages. As well, all treatments under the GF regime had similar percentages of N (Table 3-7). All GF intercrops had significantly higher proportions of N compared to their corresponding GrM intercrops. Contrasts between the GrM FP_{mono} and GF FP_{mono} showed no significant differences between these two treatments when N from Ndfa was considered as a percent of total N. As well, when the GrM FP+O3 and FP+TR treatments were compared to the GF FP+O3 and FP+TR treatments, the GF system had significantly higher N from Ndfa.

Table 3-7 Percent nitrogen derived from the atmosphere by the field pea component in the green manure (GrM) and green feed (GF) regimes at the Delisle site in 2005. The GF system was sampled 2 weeks after GrM system.

Treatment ID	Treatment Number	Ndfa†	N from Ndfa as a Percent of Total N
GrM		——kg ha^{-1}——	——%——
Field pea monocropped (FP_{mono})	2	51	59
Field pea + Oat 1 (FP+O1)§	3	41	59
Field pea + Oat 2 (FP+O2)§	4	57	63
Field pea + Oat 3 (FP+O3)§	5	59	81
Field pea + Triticale (FP+TR)	7	41	60
GF			
Field pea monocropped (FP_{mono})	9	111	75
Field pea + Oat 1 (FP+O1)§	10	120	97
Field pea + Oat 2 (FP+O2)§	11	171	88
Field pea + Oat 3 (FP+O3)§	12	140	95
Field pea + Triticale (FP+TR)	14	90	94
LSD		**54**	**12**
Orthogonal Contrasts	**Treatments compared**	***P-value***	***P-value***
GrM vs GF	2,3,4,5,7 vs 9,10,11,12,14	< 0.01*	< 0.01*
GrM FP vs GF FP	2 vs 9	0.02*	0.16
GrM intercrops vs GF intercrops	3,4,5,7 vs 10,11,12,14	< 0.01*	< 0.01*
GrM FP vs GrM intercrops	2 vs 3,4,5,7	0.94	0.43
GF FP vs GF Intercrops	9 vs 10,11,12,14	0.29	0.05
GrM FP+O3 and FP+TR vs GF FP+O3 and FP+TR	5, 7 vs 12, 14	< 0.01*	0.01*

ND = Not determined
* = Significant at $P < 0.05$ level
† = Ndfa = Nitrogen derived from the atmosphere
§ = Field pea + Oat 1, 2, 3 = 50, 100, and 150 plants m^{-2} respectively

3.4 Discussion

3.4.1 Biomass productivity at Vonda and Delisle

Green manure treatments produced lower amounts of dry matter than GF treatments presumably because they were ploughed under about two weeks earlier than GF crops. This time period allowed the GF treatments to acquire more biomass than GrM treatments, which resulted in the harvest and removal of nutrients from the system.

In order to achieve higher productivity, organic farmers must maximize top-growth and BNF while minimizing depletion of soil moisture by proper timing of GrM incorporation (AAFRD, 1993) and GF harvesting (SAF, 2004a).

Currently, the recommendation for timing GrM plough-down is at full bloom of the legume crop (SAF, 2004a). If the plough-down is conducted after full bloom, the plant material gets tougher and takes longer to decompose and release nutrients for the following crop (AAFRD, 1993). On the other hand, younger plant material may decompose more quickly after ploughing down, thus leaving the released N susceptible to leaching and volatilization (AAFRD, 1993).

In this study, GrM crops were ploughed-down about two weeks earlier than the GF crops were harvested; thus, the GF treatments had a growth advantage compared to GrM treatments. However, in terms of nutrient removal from the soil, this may have been a disadvantage. The ability of crops to acquire N from the soil and through N_2-fixation to produce biomass is dependent on several factors such as development and vigour of the root system in contact with available soil N (Thorup-Kerstensen et al., 2003), efficiency of the N_2-fixing crop (Evers, 2006), levels of available soil N, soil moisture, pH, and weather conditions (Fowler et al., 2004).

At Vonda, the Control-Wh (Table 3-5) treatment produced relatively higher biomass than GrM treatments because it also was sampled about two weeks later than GrM treatments. Wheat yield at Vonda was comparable to O_{mono} under the GF regime, but was significantly higher than the O_{mono} treatment under the GrM management system.

The TR_{mono} treatment accumulated less biomass (i.e., 688 kg ha^{-1} for GrM and 719 kg ha^{-1} for GF) than all other treatments as it grew slower than other cereals and remained a small plant through the entire growing season. This also brings to light the fact that not all cereals are the same in terms of their productivity.

Past studies have shown that intercropping legumes with cereals yielded more biomass than their monoculture counterparts (Fujita et al., 1992; Ahmad et al., 2001), although this may be dependent on other factors such as length of the growing period, temperature, and precipitation, and efficiency of the N_2-fixing crop (Evers, 2006). In this study, in the GF system, all intercrops produced more biomass than O_{mono} and TR_{mono}, but not FP_{mono}. However, the same was not true for the GrM system. This may have been because of the short growing period that the GrM system was exposed to before ploughing down. For instance, it may be that during the two week period that the GF system was allowed to grow before harvesting, would have been enough for the field pea component of the intercrop to fix more N and thus make it available to the cereal component through BNF.

Results of this study suggest that timing of the plough-down is crucial in order to maximize productivity. Our biomass results for both monocrops and intercrops were much higher than what other studies have reported (Fowler et al., 2004; Thorup-Kirstensen et al., 2003) suggesting that productivity is highly variable depending on available soil N, competitiveness of the component crops, soil moisture, and overall environmental conditions during the growing season.

Unlike the Vonda site where the monoculture FP_{mono} treatment achieved the highest biomass, O_{mono} yielded more dry matter (5758 kg ha^{-1}) than any other treatment at Delisle. Higher available soil N, especially in the lower horizon (47 kg N ha^{-1} at 30 to 45 cm) in Table 3-5 may have resulted in the largest biomass produced by the O_{mono}. Oat has a vigorous, fibrous root system that is more efficient at extracting soil N than field pea (Evers, 2006). In contrast, the slow growth and small stature of triticale appears to have compromised its biomass despite it having a fibrous root system.

At Vonda, intercropped treatments produced more biomass than their monoculture counterparts in the GrM regime. In contrast, the monoculture FP_{mono} (6095 kg ha^{-1}) produced the highest biomass in the GF regime than intercrops and other monocrops suggesting that the field pea component may have had more time to increase its biomass as well as accumulate more N from soil and through BNF before being harvested in the GF system.

The potential advantage of the intercropped system was not realised until the time of the GF harvest. For instance, at 50% flowering of the field pea, the productivity of the intercrops was similar to their monocropped counterparts. However, after two weeks of further growth, the intercropped system became more productive than monocrops. This was also seen in the percentage of N from fixation by the field pea (i.e., there was more N fixed as a percentage of the total N in the last two weeks of growth before sampling the GF system).

At Delisle, O_{mono} (Table 3-6) produced the highest biomass in both the GrM system (4238 kg ha^{-1}) and GF system (5758 kg ha^{-1}). This may suggest that because of its vigorous root system oat was able to extract available soil N whereas the oat intercrops would have been sharing the available N with its field pea component. As well, the greater soil N at Delisle resulted in more N accumulation and possibly less reliance on N_2-fixation. Past studies have reported that levels of BNF achieved are dependent on a wide range of factors such as N availability in the soil, and soil types (Evers, 2006). For example, if a legume crop is grown on a sandy soil with low N, it will derive most of its N from the air through BNF as opposed to a legume that is grown on a fertile river-bottom soil with plenty of available N (Evers, 2006). Initial soil characterization (Table 3-2) shows more NO_3-N at Delisle than at Vonda.

The combination of slow growth and small stature of triticale and lack of a vigorous fibrous root system in field pea likely resulted in significantly lower productivity of the FP+TR treatment compared to FP+O3, which had the same planting density of the cereal crop, whereas the Control-Wh treatments yielded biomass comparable to that of the intercrops. Thus, the difference in the crop structure between oat and triticale may have brought about these differences in their productivity.

In both management systems, monoculture cereals had higher C:N ratios as compared to monoculture legumes or legume-cereal intercrops. The C:N ratio can give an indication of the species and age and composition of the plant from which it is derived (Sullivan, 2003). For instance, as plants mature, the C material (fibre) increases whereas the protein material (N) decreases. It is generally agreed that the optimum C:N ratio for quick decomposition of OM is between 15:1 and 25:1 (Sullivan, 2003).

In this study, FP_{mono} and TR_{mono} had C:N ratios of 15:1 (Table 3-6). If C:N ratios are higher than 25:1, N may be immobilised by soil microorganisms as they break down plant material, thus making it unavailable to the next crop (Sullivan, 2003). For example, the wheat and oat treatments had C:N ratios of 28:1. Since most plants contain about 40% C, the C:N ratio of a crop is more a function of its N content than its C content; thus those crops with a higher N content will have a lower C:N ratio and vice versa (Sullivan, 2003). As can be seen in Table 3-6, the field pea component generally had lower C:N compared to the cereal component and the lower the C:N ratio of the crop the faster the likelihood of decomposition.

3.4.2 Nitrogen accumulation

Nitrogen accumulation by crops varies and is a function of biomass production and concentration of N (%N) in the herbage. At Vonda, all GF treatments except for the O_{mono} and TR_{mono} treatments, accumulated significantly more N than their corresponding GrM counterparts with GF FP_{mono} (161 kg N ha^{-1}) having much higher levels of accumulated N than the rest of the treatments. Compared to GF FP_{mono} (161 kg N ha^{-1}), the GrM FP_{mono} only accumulated 65 kg N ha^{-1}, although this was the highest N accumulation of all GrM treatments. These results indicate that GF field pea was actively accumulating N at the time it was ploughed down. Other studies have reported that indeterminate field pea varieties continue to grow and accumulate N throughout the growing season (SAF, 2004a). Since the 40-10 silage pea is an indeterminate variety, it can be assumed that early plough-down may have reduced the potential for adding fixed N to the GrM system whereas more N from BNF was achieved in the GF system with later harvest.

Whereas GF intercrops accumulated N amounts between 82 and 99 kg N ha^{-1}, GrM intercrops only acquired between 44 and 54 kg N ha^{-1} of N. All cereal treatments accumulated lower amounts of N ranging between 11 and 31 kg N ha^{-1}, although cereals under the GF (O_{mono} 24 kg N ha^{-1}, TR_{mono} 26 kg N ha^{-1}) regime had comparatively higher N amounts than those under the GrM regime (O_{mono} 15 kg N ha^{-1}, TR_{mono} 11 kg N ha^{-1}). These results demonstrate that on average, intercrops produced biomass and accumulated N that was intermediate between their monoculture counterparts. However, other studies have reported higher productivity of intercrops than their monoculture counterparts.

Corre-Hellou et al. (2006), Ofori and Stern (1987), and Hauggaard-Nielsen et al. (2007) reported that intercrops produced more biomass on average than their monoculture counterparts.

A study conducted in Europe on monocropped pea and intercropped pea-barley concluded that pea-barley intercrops used N sources 20 to 30% more efficiently than their monoculture counterparts (Hauggaard-Nielsen et al., 2007). Considering the N sources being soil N and N accumulated through BNF in this study, results tend to agree that intercrops were more productive than their monoculture counterparts. Higher N productivity of cereal intercrops than their monoculture cereals may have resulted from the legume component fixing more N because available soil N was depleted over time (Evers, 2006). As was expected, the GF intercrops accumulated more N because they had more time to acquire N before sampling.

All intercrops accumulated higher amounts of N compared with monocropped cereal crops, suggesting that soil N may have been made available to cereal intercrops for uptake through the NO_3^--N sparing effect of the field pea component (Szumigalski and Van Acker, 2006), as well as N supplied to the cereal component by the field pea through N_2-fixation (Corre-Hellou et al., 2006). Nitrogen sparing is reduced competition for soil NO_3^--N between the legume and cereal components. For instance, it is assumed that the legume component fixes N from the atmosphere thus, effectively "sparing" soil N sources, whereas the cereal derives its N from the soil.

At Vonda, FP_{mono} grown under GF management had the highest amount of N, likely due to the combination of higher biomass and percent N, which resulted from the length of time this treatment, grew.

At Delisle, N accumulation was significantly higher in the GF above-ground herbage compared to GrM treatments ($P < 0.05$) except for monoculture cereals (O_{mono} and TR_{mono}), which had much lower N accumulation and similar productivity under both systems (Table 3-6). The GF FP+O2 (189 kg ha^{-1}) treatment accumulated the most N suggesting the significant role intercropping plays in increasing crop biomass and consequently N uptake as accumulation of N in crops depends on dry matter production and concentration of N in the plant material. Other studies have also observed a similar trend in N amounts between pulse-cereal intercrops and their monocropped counterparts.

For instance Fowler et al. (2004), observed N amounts of 100, 126, and 162 kg N ha^{-1} for oat, oat + lupin, and lupin respectively of these cover crops before ploughing them down as GrM.

The GF FP+O1 (133 kg ha^{-1}) and FP+O3 (149 kg ha^{-1}) treatments accumulated lower N than GF FP+O2 (189 kg ha^{-1}) suggesting that a balance in the planting density of the cereal is critical in achieving the highest amount of N accumulation in an intercrop. The same scenario was observed for the GrM intercrops (Table 3-6).

The higher N accumulation in legumes and legume-cereal intercrops than monoculture cereals supports the fact that growing legumes alone and/or in combination with cereal crops helps to increase productivity of such systems whereas growing cereals alone results in poor N accumulation. For instance, despite the O_{mono} producing the highest biomass under GF management, its N accumulation was poor. However, if there is less N accumulated in the current cereal crop, this may mean that the succeeding crop may still get adequate N from the soil.

Under the GF system, the quantities of N accumulated in the above-ground plant material were 84 kg ha^{-1} for O_{mono}, between 101 and 189 kg ha^{-1} for FP+O1,2,3 or FP+TR) and 145 kg ha^{-1} for FP_{mono}, which is comparable to other studies in terms of productivity. Fowler et al. (2004) conducted a study in New Zealand on an established organic farm comparing three GrM crops [oat (*Avena sativa*), lupin (*Lupinus angustifolius*), and oat-lupin mix] and a fallow treatment for their ability to conserve N over winter and influence availability of N to a subsequent crop. They demonstrated that inclusion of GrM crops into a cereal crop rotation effectively reduced N losses associated with leaching over winter and significantly improved supply of N to the subsequent crop as compared to the fallow treatment. They reported N accumulation of 100, 126, and 162 kg N ha^{-1} for oat, oat + lupin, and lupin respectively of these cover crops before ploughing them down as GrM. Whereas Fowler et al. (2004) concluded that lupin was a suitable GrM crop in New Zealand, our results suggest that field pea, which accumulated 65 kg N ha^{-1} and 84 kg N ha^{-1} at Vonda and Delisle respectively under GrM management, may be a suitable GrM crop, especially for western Canada.

The higher productivity in biomass and N accumulation of the GF management system means that more nutrients are being exported out of the system. This usually results in soils with depleted nutrients. Although water use of the crops used in this study was not measured, it is possible that the GF system used more water compared to the GrM system, thus limiting available water for the next crop. Therefore, from a nutrient and water sustainability perspective, the GF practice may not be an ideal option or replacement for GrM management in terms of returning nutrients to the soil for subsequent crops. In semi-arid areas such as Saskatchewan, water conservation is an important aspect to take into account when growing cover crops as this has a direct effect on the subsequent crop (Biederbeck et al., 1994).

3.4.3 Percent nitrogen derived from the atmosphere (%Ndfa)

This experiment again showed that GF treatments fixed significantly more N than GrM treatments and these results reflect the fact that GrM treatments were sampled earlier than GF treatments before they had reached their full N_2-fixation potential.

It is important to time the plough-down of GrM crops in order to strike a balance between optimum N_2-fixation and conservation of soil moisture for the following crop. For instance, if ploughed down early, crops will not maximize N_2-fixation, but if ploughed down late the current crop could deplete soil moisture for the next crop (AAFRD, 1993; SAF, 2006).

This experiment did not show that increasing cereal density enhances N_2-fixation by the pea component (Table 3-7). Since the GrM treatments were sampled two weeks earlier than GF treatments, there may have been enough soil N as well as N accumulation from BNF by the field pea and thus the differences associated with N_2-fixation were not as apparent.

As for the GF treatments, which were sampled later, crops may have depleted the available soil N, thus triggering more N_2-fixation by the field pea component. For instance, Evers (2006) noted that if a legume is grown on a sandy soil with low N, it will derive most of its N from the air through N_2-fixation as opposed to a legume that is grown on a fertile river-bottom soil with plenty of available N. Thus if soil N is limited, the pulse component will acquire its N though N_2-fixation (Evers, 2006; Hauggaard-Nielsen et al., 2006). However, under both management systems, intercrops tended to fix more N than monoculture field pea, thus supporting the idea that intercropping enhances N_2-fixation compared to their monoculture counterparts (Ross et al., 2005). Jensen (1996) found that more of the N in the intercropped pea was derived from N_2-fixation than in the monocropped pea, averaging 82% and 62%, respectively. Jensen (1996) argued that the advantage in a pea-barley intercrop was mainly due to the complimentary use of soil inorganic and atmospheric N sources by the intercropped components, which resulted in reduced competition for inorganic N.

In this study intercropped field pea fixed an average of 71% and 96% or 49 kg N ha^{-1} and 130 kg N ha^{-1}, respectively, under GrM and GF management, while FP_{mono} fixed 64% and 78% (or 51 and 111 kg ha^{-1}) under the same management systems, respectively. A European intercrop project conducted in Denmark, United Kingdom, France, Germany, and Italy revealed that pea-barley intercrops used N sources 20 to 30% more efficiently than their monocultures (Hauggaard-Nielsen et al., 2006). Pea-barley intercrops in all five countries consistently fixed more N than monoculture field pea. As explained earlier, this result was likely due to the fact that soil N was made available to cereal intercrops for uptake through the NO_3^--N sparing effect of the field pea component (Szumigalski and Van Acker, 2006), as well as N supplied to the cereal component by the field pea through N_2-fixation (Corre-Hellou et al., 2006).

Pal and Shehu (2001) observed direct transfer of N from the legume to the cereal when nodulating soybean (*Glycine max* L.), lablab (*Lablab vulgaris*, L.), green gram (*Vigna radiata* L.), and black gram (*Vigna mungo* L.) were grown alone or intercropped with maize (*Zea mays* L.). Furthermore, Chalk (1998) attributed the benefit of intercropping to N-transfer, N-sparing, and less N immobilization during decomposition of the legume crop.

The fact that the GrM regime had significantly lower %Ndfa than the GF regime indicates that the early plough-down failed to capture the maximum benefits of N_2-fixation, thus re-emphasizing the fact that if the GrM management system had been given more time to grow before plough-down, its %Ndfa productivity would have been much higher. However, the semi-arid conditions in Saskatchewan generally recommend an early plough-down to conserve moisture (AAFRD, 1993; SAF, 2006).

3.5 Conclusion

Although the GF system produced significantly higher biomass and accumulated significantly higher N than the GrM system, the GrM system may still be a better option for organic farmers in terms of benefits to the soil and to subsequent crops despite the loss of income in the plough-down year. Timing of GrM incorporation is important in order to achieve the desired N yield while conserving soil moisture for the following crop. In this study the GrM management system consistently produced lower amounts of dry matter, accumulated less N, and exhibited lower N_2-fixation compared to the GF management system. This phenomenon was due to the fact that GrM treatments were sampled and ploughed down earlier than the GF treatments and this gave the GF system a longer period to grow than the GrM system. The TRmono treatments did not exhibit any allelopathic properties of suppressing weeds as this crop remained a small plant through the entire growing season.

3.6 Recommendations

This study demonstrated that not all GrM options are as productive as others. Therefore, organic farmers should seek to find out which options are suited to their soil types or options which generally have greater productivity of biomass, plant N, and higher %Ndfa, and soil N levels. In general, intercropping legumes with cereals can enhance both biomass production and N accumulation. This is an important finding for organic farmers who may rely heavily on GrM cropping.

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4 IMPACT OF GREEN MANURE AND GREEN FEED FORAGE CROPS ON SUBSEQUENT WHEAT YIELD

4.1 Introduction

Green manure (GrM) crops have the potential to improve subsequent cereal productivity and sustain agricultural systems through optimization of N gains and soil N availability. For example, Biederbeck et al. (1995) observed a greater average net N mineralization (38 kg N ha^{-1}) within three months of incorporation of lentil and chickling vetch as GrM as compared to soils that did not receive any amendments. Furthermore, they reported that an average of 48 kg N ha^{-1} that was removed through harvesting cereal grain was balanced by gains achieved through N_2-fixation by chickling vetch and field pea.

The benefits of including GrM crops either as monoculture legumes or as legume-cereal intercrops in organic cropping systems cannot be over-emphasised. For instance, a study conducted by Fowler et al. (2004) in New Zealand on an established organic farm compared three GrM crops [oat (*Avena sativa*), lupin (*Lupinus angustifolius*), and oat-lupin mix] and a fallow treatment for their ability to conserve N over winter and influence availability of N to a subsequent crop. This study demonstrated that inclusion of GrM crops into a cereal crop rotation effectively reduced N losses due to leaching over winter and significantly improved supply of N to the subsequent crop compared to the fallow treatment. It has been postulated that the abundance of soil N following legumes and legume-cereal intercrops is a result of the conservative use of N by the preceding legume and the release of mineral N by crop residues (Dalal et al., 1998). This conservative use of N by the legume crop is referred to as 'nitrate sparing' and is thought to aid the increase of soil N concentrations, thus arresting the decline of soil N fertility experienced in intensive organic cropping systems (Ahmad et al., 2001). Evans et al. (1991) and Oikeh et al. (1998) reported yield responses of cereals ranging from 50 to 80 % more after legume crops than what was achieved after cereal-cereal cropping.

Although there are obvious benefits of growing GrM crops either as monocrops or intercrops, farmers face a loss of income in the plough-down year. One option may be to grow crops as green forage (GF), so farmers may harvest (cut, dry, and bale) these crops for hay or fodder for their animals. Currently, there is little information relating to the productivity of different GrM versus GF options. A two-year rotational study was conducted to compare the productivity of GrM and GF crops and their effects on the subsequent wheat yield. In the first year (treatment year) of this study, treatments of field pea as monoculture or intercropped with oat or triticale were seeded and treated as GrM (i.e., ploughed down) or GF (i.e., harvested). Monoculture wheat and tilled fallow served as control treatments. In the second year (wheat year), wheat was seeded in all plots to evaluate its productivity following the GrM and GF treatments. This chapter reports on the second year (i.e., the wheat year).

Specific objectives of this study were to: i) compare above-ground biomass, N, and grain yield in the subsequent wheat crop following GrM and GF treatments; ii) monitor changes in soil N following wheat harvest.

4.2 Study Sites

This study was conducted at two sites (Vonda and Delisle) both located in Saskatchewan. At Vonda, the study was conducted in 2004 and 2005. At Delisle, the experiment was conducted in 2005 and 2006. The first year (treatment year) at each site consisted of 16 treatments, replicated four times in which field pea (*Pisum sativum* cv 40-10 silage pea), oat (*Avena sativa* L. cv AC Morgan) and triticale (X *Triticosecale* Wittmack cv Pika) were grown alone or in combination, and managed as either GrM or GF. In the second year (wheat year), all plots were seeded with wheat. Treatments at both sites were arranged in a randomized complete block design. Details of these study sites are described in more detail in Chapter 3.

4.3 Materials and Methods

4.3.1 Soil sampling

Soil sampling was conducted on all plots in spring following the treatment year prior to seeding to determine available inorganic N levels. Three locations were chosen at random from each plot and, using Dutch augers, cores of soils were collected at three depths (i.e., 0 to 15, 15 to 30, and 30 to 45 cm). Soils of the same depth from each of the three cores in a plot were thoroughly mixed in a bucket and a composite sample was obtained, transported to the lab, and immediately extracted using 2*M* KCl (Schoenau and

Karamanos, 1993). Soil NO_3-N and NH_4-N levels were determined according to Maynard and Kalra (1993). Here the soil NO_3-N levels are reported as inorganic N. Bulk density (BD) and moisture content (% MC) in the spring following the treatment year were determined according to Culley (1993). However, BD was determined only at the Delisle site. Therefore, average values of 1.3 for the 0- to 15- cm depths were assumed at Vonda as this BD value is widely accepted by many authorities in the literature (Culley, 1993). As for the other depths (i.e., 15 to 30 and 30 to 45 cm), BD values were assumed to be similar to those at Delisle. Intact soil cores were taken by hand from each plot in the 0 to 15 cm depth. Four plots were selected at random to sample the other two sets of depths (i.e., 15 to 30, and 30 to 45 cm) assuming that the BD for these depths would be similar. The inner diameter of the soil corer was 5 cm and its length was 15 cm.

These samples were bagged and subsequently weighed to assess the wet weight and then oven dried at 105^0C for 72 hours. The BD was calculated by dividing the sample dry weight by the core volume. By determining the wet weight and dry weight of each sample, gravimetric moisture contents were assessed for each of the samples. All samples were assessed for electrical conductivity (EC) (Jansen 1993) and soil pH (Hendershot et al., 1993) using a 1:2 soil:water extraction. Following harvest, soils were sampled again as described above, from the 0- to 15-cm depth at Vonda on September 15, 2005 and from the 0- to 15-, 15- to 30-, and 30- to 45-cm depth at Delisle on August 21, 2006. Soil sampling was conducted in the fall following final wheat harvest in all plots.

4.3.2 Plant sampling

Following the treatment year, wheat (*Triticum aestivum* L. cv AC Elsa) was seeded in all of the treatment plots in the subsequent year on May 12, 2005 at Vonda and on May 12, 2006 at Delisle (Table 4-1). All plots were sampled 30 days after planting (DAP) for biomass, N, and C yield. Sampling was conducted five times during the growing season at two weeks intervals. At each sampling time, 1-m length strips within a row were randomly selected and shoots were cut approximately 5 cm above the ground from each treatment plot using hand sickles. With a row spacing of 0.2 m, the area sampled in each plot by the end of the growing season was equivalent to 1 m^2. Samples were oven-dried for 72 h at 60^oC and weighed.

Table 4-1 Seeding and sampling dates at Vonda and Delisle in the wheat year

Site	Date	DAP†	Activity
Vonda	4 May 2005	0	Spring soil sampling
	12 May 2005	0	Seeded all plots
	20 June 2005	30	First sampling
	4 July 2005	44	Second sampling
	18 July 2005	58	Third sampling
	1 August 2005	72	Fourth sampling
	15 August 2005	86	Fifth sampling
	8 September 2005	110	Wheat grain harvest
	15 September 2005	117	Fall soil sampling
Delisle	27 April 2006	0	Spring soil sampling
	12 May 2006	0	Seeded all plots
	13 June 2006	30	First sampling
	26 June 2006	44	Second sampling
	11 July 2006	58	Third sampling
	25 July 2006	72	Fourth sampling
	9 August 2006	86	Fifth sampling
	10 August 2006	87	Wheat grain harvest
	21 August 2006	98	Fall soil sampling

† = Days after planting

Whole samples were ground for plant tissue analyses. Finally, sub-samples from the ground tissues were analysed for total N and C using a LECO CNS 2000 (LECO Corporation, St. Joseph, MI, USA) analyser.

Final grain harvest was conducted on September 8, 2005 and on August 10, 2006 at Vonda and Delisle, respectively. Plots were combined at Vonda and hand-harvested at Delisle using sickles. At Delisle, five 1-m length strips were selected randomly from each plot and shoots were cut at approximately 5 cm above ground, thus an area of 1 m^2 was sampled from each plot. These samples were bagged in cloth bags and air dried to a grain moisture content of about 13% moisture content (MC) before being threshed. The grain was ground and sub-samples analysed for N and C.

4.3.3 Statistical analyses

In this study, all data were analysed statistically using SPSS 14.0 for windows (SPSS 14.0, 2005). A one-way analysis of variance (ANOVA) was used to analyse individual and group treatments using orthogonal contrasts. The least significant differences (LSD) were determined by using pair-wise comparison of group means i.e., mean squares (MS) error within groups and degrees of freedom for error within groups. A detailed outline of all statistical tests applied in this study is given in chapter 3. The following equation was used to calculate LSD values in this study:

$$LSD_{0.05} = t_{0.05}\sqrt{2MS/n} \qquad [4.1];$$

where t = tabular t value for degrees of freedom for error, MS = mean squares for error within groups, n = number of treatment replicates.

4.4 Results

Treatments used in this study are abbreviated as follows: Tilled fallow-control (Control-SF), wheat-control (Control-Wh), field pea monocropped (FP_{mono}), field pea + oat 1,2,3 (FP+O1,2,3), oat monocropped (O_{mono}), field pea + triticale (FP+TR), triticale monocropped (TR_{mono}). Average temperatures were similar for both years and were comparable to the 30 year average temperatures whereas the total rainfall was 88 mm more in 2005 than in 2006 (Table 4-2). However, the total precipitation for 2006 was 24 mm more than the 30 year average. At both sites, there was more rainfall in June compared to other months.

Table 4-2 Spring and summer weather data as recorded at the Saskatoon international airport for Vonda in 2005 and Delisle in 2006

Precipitation (mm)			
Month	**30 year average**†	**2005** Vonda	**2006** Delisle
May	20	28	39
June	44	161	108
July	63	54	32
August	58	54	30
Average	46	74	74
Total	**185**	**297**	**209**

Mean daily temperature (^{0}C)			
	30 year average†	**2004** Vonda	**2005** Delisle
May	11.5	10.0	11.5
June	16.0	14.5	16.0
July	18.2	17.5	20.0
August	17.3	15.5	18.0

† = Based on Saskatoon weather data from 1971-2000 from Environmental Canada

4.4.1 Spring soil nitrogen levels following GrM and GF treatments

At Vonda, plots following GrM incorporation had significantly higher levels of soil N than plots after the GF system at all three sampling depths (Table 4-3). At all three soil depths, the GrM FP_{mono} retained the highest amount of soil N, followed by GrM FP+O1 and Control-SF. Plots following the Control-SF treatments were significantly higher than those following the GrM system at 15- to 30-, and 30- to 45-cm depths.

In the GF system, only the plots following FP_{mono} had significantly higher soil N levels than the other plots at all three soil depths *($P < 0.05$)*. Differences were also observed between GrM versus Control-Wh and GF versus Control-SF in which the plots following the GrM and Control-SF had greater soil inorganic N respectively. There were no differences between plots following the GF versus Control-Wh and between plots following the GrM intercrop versus GF intercrops. Plots following triticale yielded the lowest amounts of N in both GrM and GF systems and at all three soil depths.

At Delisle, similar to the Vonda site, significant differences were observed between the GrM and GF plots at the 0- to 15-, 15- to 30-, and 30- to 45-cm depths, *($P < 0.05$)* with the former having more soil N than the latter (Table 4-4). When the 0- to 45-cm depth was considered, the GrM FP_{mono} retained the highest amount of soil N. Of particular interest was the GrM FP+TR treatment, which returned significantly more N to the soil, compared with the GrM FP+O3 treatment (same cereal density), at all the three soil sampling depths. The Control-SF had significantly higher soil N than the GF system only at the 0- to 15-cm depth whereas there were no significant differences between the GF management regime and the control-Wh system at all three soil depths *($P < 0.05$)* (Table 4-4).

4.4.2 Wheat biomass production at Vonda

Significant differences in wheat biomass productivity between treatments following GrM and GF systems were observed as early as 30 DAP and continued for the remainder of the sampling period (Table 4-5). Starting at 30 DAP, wheat treatments following GrM produced significantly more biomass than their corresponding GF counterparts throughout the growing season.

Table 4-3 Spring soil inorganic N (NO_3-N) levels following GrM incorporation, GF harvesting, tilled fallow-control and wheat-control harvest at Vonda in 2005

Stubble Treatments	**Treatment Number**	**Depth (cm)**			
		0-15	15-30	30-45	0-45
		NO_3-N (kg ha^{-1})			
Control-SF†	1	20.0	20.0	29.0	70.0
Control-Wh‡	16	13.0	12.0	14.0	40.0
Green Manure (GrM)					
Field pea monocropped (FP_{mono})	2	21.0	25.0	36.0	82.0
Field pea + oat 1 (FP+O1)§	3	25.0	20.0	28.0	73.0
Field pea + oat 2 (FP+O2)§	4	16.0	15.0	19.0	50.0
Field pea + oat 3 (FP+O3)§	5	16.0	14.0	19.0	49.0
Oat monocropped (O_{mono})	6	16.0	14.0	18.0	48.0
Field pea + triticale (FP+TR)	7	15.0	13.0	15.0	42.0
Triticale monocropped (TR_{mono})	8	11.0	12.0	11.0	34.0
Green Feed Forage (GF)					
Field pea monocropped (FP_{mono})	9	18.0	20.0	20.0	58.0
Field pea + oat 1 (FP+O1)§	10	14.0	12.0	13.0	39.0
Field pea + oat 2 (FP+O2)§	11	14.0	12.0	13.0	39.0
Field pea + oat 3 (FP+O3)§	12	14.0	14.0	14.0	41.0
Oat monocropped (O_{mono})	13	13.0	9.0	12.0	34.0
Field pea + triticale (FP+TR)	14	10.0	9.0	11.0	30.0
Triticale monocropped (TR_{mono})	15	10.0	10.0	10.0	25.0
LSD		**3**	**3**	**4**	ND
Orthogonal Contrasts	**Treatments Compared**	***2-tailed sig.***			
GrM vs. GF	2,3,4,5,6,7,8 vs. 9,10,11,12,13,14,15	< 0.01*	< 0.01*	< 0.01*	ND
GrM vs. Control-SF	2,3,4,5,6,7,8 vs. 1	0.17	< 0.04*	< 0.01*	ND
GrM vs. Control-Wh	2,3,4,5,6,7,8 vs 16	0.04*	0.02*	< 0.01*	ND
GF vs. Control-SF	9,10,11,12,13,14,15 vs. 1	0.01*	< 0.01*	< 0.01*	ND
GF vs. Control-Wh	9,10,11,12,13,14,15 vs 16	0.85	0.70	0.57	ND
GrM intercrops vs. GF intercrops	3,4,5,7 vs. 10,11,12,14	0.71	0.51	0.13	ND

ND = Not determined
* = Significant at $P < 0.05$ level
† = Tilled fallow-control
‡ = Wheat-control
§ = Field pea + oat 1,2,3 = 50, 100, & 150 plants m^{-2} respectively

Table 4-4 Spring soil inorganic N (NO_3-N) levels following GrM incorporation, GF harvesting, tilled fallow-control and wheat harvest at Delisle in 2006

Stubble Treatments	Treatment Number	Depth (cm)			
		0-15	15-30	30-45	0-45
		NO_3-N (kg ha^{-1})			
Control-SF†	1	80.0	38.0	37.0	150.0
Control-Wh‡	16	11.0	15.0	18.0	43.0
Green Manure (GrM)					
Field pea monocropped (FP_{mono})	2	67.0	52.0	44.0	163.0
Field pea + oat 1 (FP+O1)§	3	44.0	28.0	33.0	105.0
Field pea + oat 2 (FP+O2)§	4	13.0	25.0	29.0	67.0
Field pea + oat 3 (FP+O3)§	5	13.0	26.0	33.0	72.0
Oat monocropped (O_{mono})	6	11.0	20.0	24.0	55.0
Field pea + triticale (FP+TR)	7	31.0	35.0	36.0	102.0
Triticale monocropped (TR_{mono})	8	10.0	21.0	20.0	51.0
Green Feed Forage (GF)					
Field pea monocropped (FP_{mono})	9	14.0	27.0	50.0	91.0
Field pea + oat 1 (FP+O1)§	10	12.0	24.0	27.0	63.0
Field pea + oat 2 (FP+O2)§	11	12.0	19.0	31.0	62.0
Field pea + oat 3 (FP+O3)§	12	13.0	22.0	28.0	63.0
Oat monocropped (O_{mono})	13	12.0	22.0	21.0	55.0
Field pea + triticale (FP+TR)	14	10.0	17.0	18.0	45.0
Triticale monocropped (TR_{mono})	15	6.0	7.0	10.0	23.0
LSD		**3**	**3**	**3**	ND
Orthogonal Contrasts	**Treatments Compared**	***2-tailed sig.***			
GrM vs. GF	2,3,4,5,6,7,8 vs. 9,10,11,12,13,14,15	0.04*	0.01*	0.04*	ND
GrM vs. Control-SF	2,3,4,5,6,7,8 vs. 1	0.01*	0.75	0.77	ND
GrM vs. Control-Wh	2,3,4,5,6,7,8 vs 16	0.33	0.13	0.14	ND
GF vs. Control-SF	9,10,11,12,13,14,15 vs. 1	< 0.01*	0.34	0.50	ND
GF vs. Control-Wh	9,10,11,12,13,14,15 vs 16	0.99	0.79	0.61	ND
GrM intercrops vs. GF intercrops	3,4,5,7 vs. 10,11,12,14	0.42	0.72	0.90	ND

ND = Not determined
* = Significant at $P < 0.05$ level
† = Tilled fallow-control
‡ = Wheat-control
§ = Field pea + oat 1,2,3 = 50, 100, & 150 plants m^{-2} respectively

Table 4-5 Mean wheat biomass accumulation at Vonda in 2005 (Year 2) following green manure (GrM) and green feed forage (GF) treatments the previous year

Stubble Treatments	**Treatment Number**	**Sampling Time (DAP§§)**				
		30	**44**	**58**	**72**	**86**
		Wheat Biomass (kg ha^{-1})				
Control-SF†	1	357	3074	4725	6213	6175
Control-Wh‡	16	311	1888	3375	3275	3138
Green Manure (GrM)						
Field pea monocropped (FP_{mono})	2	528	3328	4825	7350	7113
Field pea + oat 1 (FP+O1)§	3	363	2537	3438	4825	4638
Field pea + oat 2 (FP+O2)§	4	337	2621	4025	4638	4888
Field pea + oat 3 (FP+O3)§	5	385	2903	4438	4075	4825
Oat monocropped (O_{mono})	6	489	2737	3550	4488	4650
Field pea + triticale (FP+TR)	7	360	2399	4200	4100	3588
Triticale monocropped (TR_{mono})	8	374	2064	3688	3400	2888
Green Feed Forage (GF)						
Field pea monocropped (FP_{mono})	9	359	2599	4338	5325	4950
Field pea + oat 1 (FP+O1)§	10	306	2371	3400	3850	2663
Field pea + oat 2 (FP+O2)§	11	329	2137	4275	3750	3513
Field pea + oat 3 (FP+O3)§	12	293	2172	3538	3088	3388
Oat monocropped (O_{mono})	13	294	1802	2338	2838	2850
Field pea + triticale (FP+TR)	14	253	1610	3175	2938	2375
Triticale monocropped (TR_{mono})	15	192	1596	1738	2525	2150
LSD		**187**	**707**	**2238**	**1595**	**1983**
Orthogonal Contrasts	**Treatments Compared**	***P-value (2-tailed sig.)***				
GrM vs. GF	2,3,4,5,6,7,8 vs. 9,10,11,12,13,14,15	< 0.01*	< 0.01*	0.04*	< 0.01*	< 0.01*
GrM vs. Control-SF	2,3,4,5,6,7,8 vs. 1	0.44	0.07	0.34	0.01*	0.02*
GrM vs. Control-Wh	2,3,4,5,6,7,8 vs. 16	0.13	< 0.01*	0.38	0.01*	0.02*
GF vs. Control-SF	9,10,11,12,13,14,15 vs. 1	0.27	< 0.01*	0.05	< 0.01*	< 0.01*
GF vs. Control-Wh	9,10,11,12,13,14,15 vs. 16	0.26	0.22	0.35	0.06	0.08
GrM intercrops vs. GF intercrops	3,4,5,7 vs. 10,11,12,14	0.11	< 0.01*	0.38	0.01*	< 0.01*

* = Significant at $P < 0.05$ level
† = Tilled fallow-control
‡ = Wheat-control
§ = Field pea + oat 1,2,3 = 50, 100, & 150 plants m^{-2} respectively
§§ = Days after planting.

Wheat following FP_{mono} accumulated the most biomass in each system (Table 4-5). As well, wheat following GrM FP_{mono} (7350 kg ha^{-1} at 72 DAP) accumulated the most biomass compared to all other treatments followed by wheat after Control-SF (6213 kg ha^{-1} at 72 DAP).

Significant differences between wheat following the GrM system and wheat following Control-SF were only observed at 72 and 86 DAP, where wheat after the Control-SF system performed better than that following the GrM regime (Table 4-5). Wheat biomass following the GrM system was significantly higher at 44, 72, and 86 DAP than wheat biomass after Control-Wh. Wheat following GrM and GF TR_{mono} produced the least amount of biomass of all treatments. Significant differences between wheat following GF treatments versus wheat following Control-SF were noticed at 44, 72, and 86 DAP (with wheat after Control-SF being significantly higher than wheat after GF). There were no significant differences between wheat following the GF system versus wheat after Control-Wh. However, significant differences were observed at 44, 72, and 86 DAP, between wheat treatments following GrM intercrops versus GF intercrops, with the former being significantly higher than the latter (Table 4-5).

4.4.3 Wheat biomass production at Delisle

At Delisle, differences in wheat productivity between treatments following GrM and GF were observed at 58, 72, and 86 DAP (Table 4-6). Treatments following the GrM system produced more biomass than wheat following the GF system. There were no significant differences between wheat following the GrM system and that following the Control-SF system. On the other hand, there were significant differences between the GrM system versus the Control-Wh at the 44, 58, and 72 DAP.

Differences between wheat following the GF system and that following Control-SF were only observed at 58 and 86 DAP and at 58 and 72 DAP between GF versus Control-Wh. Wheat following TR_{mono} treatments under GrM and GF regimes had comparatively lower biomass than the rest of the treatments in the two management systems.

Table 4-6 Mean wheat biomass accumulation at Delisle in 2006 (Year 2) following green manure (GrM) and green feed forage (GF) treatments the previous year

Stubble Treatments	**Treatment Number**	**Sampling Time (DAP[§§])**				
		30	**44**	**58**	**72**	**86**
		Wheat Biomass (kg ha^{-1})				
Control-SF[†]	1	256	1834	5038	6413	5225
Control-Wh[‡]	16	263	1151	2600	2913	3438
Green Manure (GrM)						
Field pea monocropped (FP_{mono})	2	268	1582	4213	5588	5838
Field pea + oat 1 (FP+O1)[§]	3	370	1991	4763	6000	5125
Field pea + oat 2 (FP+O2)[§]	4	286	1786	3925	5775	4175
Field pea + oat 3 (FP+O3)[§]	5	274	1790	4750	6563	4288
Oat monocropped (O_{mono})	6	284	1677	3938	6475	5300
Field pea + triticale (FP+TR)	7	238	1350	3775	5738	4575
Triticale monocropped (TR_{mono})	8	246	1239	3475	4775	3663
Green Feed Forage (GF)						
Field pea monocropped (FP_{mono})	9	268	1591	3988	5975	4288
Field pea + oat 1 (FP+O1)[§]	10	292	1650	4475	4838	4775
Field pea + oat 2 (FP+O2)[§]	11	293	1947	3150	5113	3513
Field pea + oat 3 (FP+O3)[§]	12	306	1496	4050	5650	2875
Oat monocropped (O_{mono})	13	248	1411	3550	4613	3063
Field pea + triticale (FP+TR)	14	261	1292	3175	4525	3163
Triticale monocropped (TR_{mono})	15	177	893	2950	3913	2163
LSD		**132**	**712**	**1447**	**2305**	**2037**
Orthogonal Contrasts	**Treatments Compared**	***P-value (2-tailed sig.)***				
GrM vs. GF	2,3,4,5,6,7,8 vs. 9,10,11,12,13,14,15	0.42	0.17	0.03*	0.02*	< 0.01*
GrM vs. Control-SF	2,3,4,5,6,7,8 vs. 1	0.57	0.39	0.06	0.45	0.44
GrM vs. Control-Wh	2,3,4,5,6,7,8 vs. 16	0.68	0.04*	< 0.01*	< 0.01*	0.06
GF vs. Control-SF	9,10,11,12,13,14,15 vs. 1	0.86	0.12	< 0.01*	0.06	0.01*
GF vs. Control-Wh	9,10,11,12,13,14,15 vs. 16	0.54	0.06	0.04*	< 0.01*	0.08
GrM intercrops vs. GF intercrops	3,4,5,7 vs. 10,11,12,14	0.88	0.39	0.06	0.05	0.03*

* = Significant at $P < 0.05$ level
† = Tilled fallow-control
‡ = Wheat-control
§ = Field pea + oat 1,2,3 = 50, 100, & 150 plants m^{-2} respectively
§§ = Days after planting

At this site (Delisle), biomass increased from the first sampling (30 DAP) to the fourth sampling (72 DAP) before starting to decrease at the fifth sampling (86 DAP) as dry leaves were dropping off from plants (Table 4-6). However, wheat following FP_{mono} and Control-Wh peaked at the fifth sampling time (86 DAP) (i.e., 5838 kg ha^{-1} and 3438 kg ha^{-1}, respectively). By the fourth sampling date (72 DAP), which was the highest biomass accumulation stage for most treatments, wheat following the FP+O3 treatment under GrM had the highest accumulation of 6563 kg ha^{-1} followed by wheat after GrM O_{mono} at 6475 kg $ha^{-1}$and wheat after Control-SF at 6413 kg ha^{-1}, although differences between treatments were not significant. The GF system versus Control-SF showed differences at 58 and 86 DAP, whereas GF versus Control-Wh showed differences at 58 and 72 DAP. At 58 and 86 DAP, wheat biomass following the Control-SF system was more than wheat following the GF system whereas wheat following the GF system had more biomass than wheat after the Control-Wh at 58 and 72 DAP. However, there were no significant differences in wheat biomass following intercrops under each management system except at the fifth (86 DAP) sampling where wheat following the GrM intercrops had more biomass (Table 4-6).

4.4.4 Wheat nitrogen accumulation at Vonda

Nitrogen accumulation in wheat following GrM and GF treatments followed a similar trend as wheat biomass production (Table 4-7). Significant differences were observed for the first two sampling periods as well as the last sampling between GrM and GF systems. Here, treatments following the GrM management system had higher N accumulation than those following the GF regime. There were no differences in N between wheat following GrM versus Control-SF.

Differences between wheat following the GF system versus that following the Control-SF were observed at the 44, 58, and 86 DAP, where wheat following the Control-SF system accumulated more N that wheat following the GF system. There were no significant differences between wheat following the GF system versus wheat after Control-Wh. Except for treatments following O_{mono} under both GrM and GF systems, treatments following Control-Wh and TR_{mono} had the least N accumulation whereas those treatments following intercrops were intermediate (Table 4-7).

Table 4-7 Mean wheat N accumulation at Vonda in 2005 (Year 2) following green manure (GrM) and green feed forage (GF) treatments the previous year

Stubble Treatments	Treatment Number	Sampling Time (DAP§§)				
		30	**44**	**58**	**72**	**86**
		Wheat Total N (kg ha^{-1})				
Control-SF†	1	15	53	65	40	38
Control-Wh‡	16	11	26	38	23	22
Green Manure (GrM)						
Field pea monocropped (FP_{mono})	2	23	69	60	46	57
Field pea + oat 1 (FP+O1)§	3	15	46	42	28	29
Field pea + oat 2 (FP+O2)§	4	13	39	46	29	32
Field pea + oat 3 (FP+O3)§	5	16	51	55	27	28
Oat monocropped (O_{mono})	6	18	36	42	30	35
Field pea + triticale (FP+TR)	7	14	40	50	31	28
Triticale monocropped (TR_{mono})	8	13	24	40	24	26
Green Feed Forage (GF)						
Field pea monocropped (FP_{mono})	9	14	39	55	34	35
Field pea + oat 1 (FP+O1)§	10	11	30	44	24	21
Field pea + oat 2 (FP+O2)§	11	11	28	49	25	24
Field pea + oat 3 (FP+O3)§	12	11	32	38	23	25
Oat monocropped (O_{mono})	13	10	20	27	27	31
Field pea + triticale (FP+TR)	14	10	20	42	26	20
Triticale monocropped (TR_{mono})	15	6	23	23	28	29
LSD		**20**	**18**	**30**	**14**	**17**
Orthogonal Contrasts	**Treatments Compared**	***P-value (2-tailed sig.)***				
GrM vs. GF	2,3,4,5,6,7,8 vs. 9,10,11,12,13,14,15	< 0.01*	< 0.01*	0.10	0.07	0.01*
GrM vs. Control-SF	2,3,4,5,6,7,8 vs. 1	0.62	0.12	0.08	0.05	0.40
GrM vs. Control-Wh	2,3,4,5,6,7,8 vs. 16	0.06	0.04*	0.33	0.09	0.04*
GF vs. Control-SF	9,10,11,12,13,14,15 vs. 1	0.10	< 0.01*	0.01*	0.05	0.04*
GF vs. Control-Wh	9,10,11,12,13,14,15 vs. 16	0.61	0.06	0.44	0.33	0.06
GrM intercrops vs. GF intercrops	3,4,5,7 vs. 10,11,12,14	0.03*	< 0.01*	0.44	0.15	0.08

* = Significant at $P < 0.05$ level, ‡ = DAP = Days after planting
† = Tilled fallow-control
‡ = Wheat-control
§ = Field pea + oat 1,2,3 = 50, 100, & 150 plants m^{-2} respectively
§§ = Days after planting

At 58 DAP, wheat N accumulation following intercrops under both GrM and GF systems was intermediate between that following FP_{mono} and cereals. Significant differences between wheat following GrM intercrops versus wheat following GF intercrops were only observed at 30 and 44 DAP. As well, when wheat following FP+O3 versus FP+TR (same planting density) under both GrM and GF regimes were considered, there were no significant differences between these treatments in their categories (Table 4-7).

4.4.5 Wheat nitrogen accumulation at Delisle

Similar to the wheat at Vonda, wheat at Delisle increased its N accumulation from 30 DAP and peaked at 58 DAP after which it decreased as dead and drying leaves were falling off at this growth stage (Table 4-8). Although there were no significant differences at 30 and 44 DAP between treatments following the GrM and GF regime, the last three samplings did show significant differences between treatments following the two regimes where wheat grown after the GrM treatments accumulated more N than wheat following the GF system. Significant differences were observed from the 58, 72 and 86 DAP between wheat following GrM versus GF, GrM versus Control-SF, and GrM intercrops versus GF intercrops. There were no significant differences between wheat following Control-SF treatments and wheat following the GrM FP_{mono} treatments. Wheat following GrM and GF intercrops was intermediate between FP_{mono} and monoculture cereals within their respective regimes.

Generally, wheat following monocropped cereals accumulated consistently less N compared to the other treatments, although wheat following O_{mono} under GrM accumulated comparatively higher N. Wheat following TR_{mono} under both GrM and GF had similar N accumulation to wheat following the Control-Wh treatments. At 58, 72, and 86 DAP, wheat following the control-SF had higher N than wheat following the GF system. Differences were observed between wheat following the GF system versus wheat following the Control-Wh, where wheat following the GF system accumulated more N. Moreover, at 58, 72, and 86 DAP, wheat following GrM intercrops accumulated significantly more N than wheat following GF intercrops (Table 4-8).

Table 4-8 Mean wheat N accumulation at Delisle in 2006 (Year 2) following green manure (GrM) and green feed forage (GF) treatments the previous year

Stubble Treatments	**Treatment Number**	**Sampling Time (DAP§§)**				
		30	**44**	**58**	**72**	**86**
		Wheat Total N (kg ha^{-1})				
Control-SF†	1	13	82	137	90	51
Control-Wh‡	16	12	33	40	22	16
Green Manure (GrM)						
Field pea monocropped (FP_{mono})	2	13	73	111	96	57
Field pea + oat 1 (FP+O1)§	3	15	73	110	80	39
Field pea + oat 2 (FP+O2)§	4	14	72	91	73	32
Field pea + oat 3 (FP+O3)§	5	14	77	108	79	35
Oat monocropped (O_{mono})	6	14	55	79	69	38
Field pea + triticale (FP+TR)	7	12	58	108	86	39
Triticale monocropped (TR_{mono})	8	12	49	74	48	24
Green Feed Forage (GF)						
Field pea monocropped (FP_{mono})	9	13	67	94	74	33
Field pea + oat 1 (FP+O1)§	10	14	64	89	48	27
Field pea + oat 2 (FP+O2)§	11	15	73	68	47	21
Field pea + oat 3 (FP+O3)§	12	15	59	81	56	18
Oat monocropped (O_{mono})	13	12	52	69	48	18
Field pea + triticale (FP+TR)	14	13	48	64	48	20
Triticale monocropped (TR_{mono})	15	8	33	61	44	15
LSD		**7**	**28**	**33**	**29**	**13**
Orthogonal Contrasts	**Treatments Compared**	***P-value (2-tailed sig.)***				
GrM vs. GF	2,3,4,5,6,7,8 vs. 9,10,11,12,13,14,15	0.61	0.07	< 0.01*	< 0.01*	< 0.01*
GrM vs. Control-SF	2,3,4,5,6,7,8 vs. 1	0.77	0.08	< 0.01*	0.14	< 0.01*
GrM vs. Control-Wh	2,3,4,5,6,7,8 vs 16	0.52	< 0.01*	< 0.01*	< 0.01*	< 0.01*
GF vs. Control-SF	9,10,11,12,13,14,15 vs. 1	0.97	0.01	< 0.01*	< 0.01*	< 0.01*
GF vs. Control-Wh	9,10,11,12,13,14,15 vs. 16	0.52	0.01*	< 0.01*	< 0.01*	0.04*
GrM intercrops vs. GF intercrops	3,4,5,7 vs. 10,11,12,14	0.78	0.16	< 0.01*	< 0.01*	< 0.01*

* = Significant at $P < 0.05$ level
† = Tilled fallow-control
‡ = Wheat-control
§ = Field pea + oat 1,2,3 = 50, 100, & 150 plants m^{-2} respectively,§§ = Days after planting

4.4.6 Wheat grain yield and nitrogen accumulation at Vonda

Wheat following the GrM system produced significantly more grain biomass and accumulated more N than wheat following the GF system (Table 4-9). Wheat following Control-SF had significantly higher yield than wheat following both the GrM and GF systems. Wheat grown after the GrM system produced more grain and accumulated more N than wheat following Control-Wh. Grain productivity was highest in treatments following GrM FP_{mono} and wheat grown after the Control-SF system, which had similar productivity. Wheat grown after the GrM intercrops had better yield compared to wheat following GF intercrops.

Wheat following the GrM intercrops yielded better than wheat following GrM cereal monocrops and Control-Wh treatments. Similarly, wheat following GF FP_{mono} treatments had significantly higher grain yield than all other treatments following GF treatments with the exception of FP+O1, where differences was not statistically significant. Wheat following the Control-SF system produced significantly more grain yield compared to wheat after the GrM and GF systems. As well, wheat following GF intercrops produced more grain yield than wheat following monocropped cereals. However, wheat following both the GrM and GF TR_{mono} produced the least amount of grain (Table 4-9).

Wheat following GrM FP_{mono} had the highest N accumulation followed by wheat grown after the Control-SF (Table 4-9). Overall, wheat following the GrM regime again had significantly higher N accumulation than wheat following is GF counterpart. Wheat grain following the GrM system had similar N with wheat grain following the Control-SF system, but significantly higher than wheat grain following the Control-Wh system. All wheat plots following GrM intercrops accumulated significantly more N than wheat plots following their monoculture cereal counterparts. Similarly, Wheat following GF intercrops performed better than wheat following their monoculture cereal counterparts. Wheat following the Control-SF system had significantly higher grain N than wheat following the GF system. However, there were no differences between wheat grain N following the GF system and wheat following the Control-Wh system. Furthermore, significant differences were observed between wheat grain N following the GrM intercrops and that following the GF intercrops (Table 4-9).

Table 4-9 Wheat grain yield and total nitrogen following green manure (GrM) and green feed forage (GF) treatments at Vonda in 2005 (Year 2)

Stubble Treatments	Treatment Number	Grain Yield	Grain Total N
		kg ha^{-1}	
Control-SF[†]	1	1500	30
Control-Wh[‡]	16	742	15
Green Manure (GrM)			
Field pea monocropped (FP_{mono})	2	1815	40
Field pea + oat 1 (FP+O1)[§]	3	1365	28
Field pea + oat 2 (FP+O2)[§]	4	1221	24
Field pea + oat 3 (FP+O3)[§]	5	1106	22
Oat monocropped (O_{mono})	6	1090	22
Field pea + triticale (FP+TR)	7	992	19
Triticale monocropped (TR_{mono})	8	785	17
Green Feed Forage (GF)			
Field pea monocropped (FP_{mono})	9	1210	25
Field pea + oat 1 (FP+O1)[§]	10	869	18
Field pea + oat 2 (FP+O2)[§]	11	767	16
Field pea + oat 3 (FP+O3)[§]	12	783	16
Oat monocropped (O_{mono})	13	575	12
Field pea + triticale (FP+TR)	14	567	12
Triticale monocropped (TR_{mono})	15	498	11
LSD		**383**	**9**
Orthogonal Contrasts	**Treatments Compared**	***P-value (2-tailed sig.)***	
GrM vs. GF	2,3,4,5,6,7,8 vs. 9,10,11,12,13,14,15	< 0.01*	< 0.01*
GrM vs. Control-SF	2,3,4,5,6,7,8 vs. 1	0.02*	0.05
GrM vs. Control-Wh	2,3,4,5,6,7,8 vs 16	< 0.01*	< 0.01*
GF vs. Control-SF	9,10,11,12,13,14,15 vs. 1	< 0.01*	< 0.01*
GF vs. Control-Wh	9,10,11,12,13,14,15 vs. 16	0.33	0.32
GrM intercrops vs. GF intercrops	3,4,5,7 vs. 10,11,12,14	< 0.01*	< 0.01*

* = Significant at $P < 0.05$ level,
† = Tilled fallow-control,
‡ = Wheat-control,
§ = Field pea + oat 1,2,3 = 50, 100, & 150 plants m^{-2} respectively.

4.4.7 Wheat grain yield and nitrogen accumulation at Delisle

At the Delisle site, wheat grain productivity following the GrM system and the GF system were similar (Table 4-10). As well, there were differences in wheat grain biomass following the GrM and Control-SF treatments. However, when wheat grain biomass following the GrM system and that following the Control-Wh system was considered, wheat following the GrM system had significantly higher grain biomass. Wheat grain biomass following the GF system and that following the Control-SF was similar. Wheat grain biomass following the GF system was significantly higher than wheat grain biomass following the Control-Wh system. Furthermore, when wheat grain biomass following GrM and GF intercrops was considered, there were no significant differences between these two sets.

When grain total N was considered, there were significant differences between wheat following the GrM management and the GF management system, where the wheat following the GrM system had more grain N than wheat after the GF system (Table 4-10). Wheat grain N accumulation was similar between wheat grown after the GrM system and that following the Control-SF system. Wheat grain N accumulation following the GrM regime was significantly higher than that following the Control-Wh system. On the other hand, grain N accumulation was significantly higher following the Control-SF system compared to wheat following the GF system. As well, wheat following GrM intercrops accumulated significantly more N than their GF counterparts, although their grain biomass was not significantly different. Similar to the wheat grain biomass productivity, wheat following Control-Wh treatments accumulated the least amount of N (Table 4-10).

4.4.8 Fall soil data at Vonda and Delisle

By the end of the second cycle (i.e., following wheat harvest) soil N levels were considerably lower in all plots than N levels following GrM and GF treatments (Table 4-11). There were no significant differences at the Vonda site among treatments within each system and between both systems and the controls. At Vonda, only the 0- to 15-cm soils were sampled. Here, N levels in the soil were considerably lower than those obtained at the Delisle site.

Table 4-10 Wheat grain biomass and total nitrogen following green manure (GrM) and green feed forage (GF) treatments at Delisle in 2006

Stubble Treatments	Treatment Number	Grain Yield	Grain Total N
		—kg ha^{-1}—	
Control-SF[†]	1	1354	41
Control-Wh[‡]	16	558	12
Green Manure (GrM)			
Field pea monocropped (FP_{mono})	2	1290	40
Field pea + oat 1 (FP+O1)[§]	3	1103	32
Field pea + oat 2 (FP+O2)[§]	4	1410	39
Field pea + oat 3 (FP+O3)[§]	5	1202	34
Oat monocropped (O_{mono})	6	1076	26
Field pea + triticale (FP+TR)	7	1132	34
Triticale monocropped (TR_{mono})	8	855	22
Green Feed Forage (GF)			
Field pea monocropped (FP_{mono})	9	1047	31
Field pea + oat 1 (FP+O1)[§]	10	1290	34
Field pea + oat 2 (FP+O2)[§]	11	996	26
Field pea + oat 3 (FP+O3)[§]	12	808	21
Oat monocropped (O_{mono})	13	924	22
Field pea + triticale (FP+TR)	14	839	22
Triticale monocropped (TR_{mono})	15	601	15
LSD		**670**	**16**
Orthogonal Contrasts	**Treatments Compared**	—***P-value (2-tailed sig.)***—	
GrM vs. GF	2,3,4,5,6,7,8 vs. 9,10,11,12,13,14,15	0.05	< 0.01*
GrM vs. Control-SF	2,3,4,5,6,7,8 vs. 1	0.36	0.08
GrM vs. Control-Wh	2,3,4,5,6,7,8 vs. 16	0.01*	< 0.01*
GF vs. Control-SF	9,10,11,12,13,14,15 vs. 1	0.06	< 0.01*
GF vs. Control-Wh	9,10,11,12,13,14,15 vs. 16	0.04*	< 0.01*
GrM intercrops vs. GF intercrops	3,4,5,7 vs. 10,11,12,14	0.12	0.01*

* = Significant at $P < 0.05$ level,
† = Tilled fallow-control,
‡ = Wheat-control,
§ = Field pea + oat 1,2,3 = 50, 100, & 150 plants m^{-2} respectively.

Table 4-11 Fall soil inorganic N (NO_3-N) levels at Vonda in 2005 and at Delisle in 2006 following final wheat harvest

Stubble Treatments	**Treatment Number**	**Delisle**				**Vonda**
		Depth (cm)				
		0-15	**15-30**	**30-45**	**0-45**	**0-15**
		NO_3-N (kg ha^{-1})				
Control-SF†	1	8.0	11.0	12.0	32.0	8.0
Control-Wh‡	16	5.0	3.0	4.0	12.0	9.0
Green Manure (GrM)						
Field pea monocropped (FP_{mono})	2	10.0	10.0	23.0	43.0	9.0
Field pea + oat 1 (FP+O1)§	3	10.0	8.0	16.0	34.0	7.0
Field pea + oat 2 (FP+O2)§	4	10.0	4.0	3.0	17.0	9.0
Field pea + oat 3 (FP+O3)§	5	7.0	10.0	12.0	28.0	7.0
Oat monocropped (O_{mono})	6	9.0	4.0	5.0	18.0	9.0
Field pea + triticale (FP+TR)	7	11.0	9.0	15.0	35.0	9.0
Triticale monocropped (TR_{mono})	8	8.0	5.0	6.0	19.0	9.0
Green Feed Forage (GF)						
Field pea monocropped (FP_{mono})	9	6.0	4.0	4.0	13.0	9.0
Field pea + oat 1 (FP+O1)§	10	7.0	6.0	4.0	16.0	9.0
Field pea + oat 2 (FP+O2)§	11	5.0	4.0	6.0	15.0	10.0
Field pea + oat 3 (FP+O3)§	12	5.0	4.0	5.0	14.0	9.0
Oat monocropped (O_{mono})	13	5.0	3.0	2.0	10.0	8.0
Field pea + triticale (FP+TR)	14	4.0	4.0	3.0	11.0	8.0
Triticale monocropped (TR_{mono})	15	4.0	3.0	2.0	9.0	9.0
LSD		**4**	**4**	**9**		**1**
Orthogonal Contrasts	**Treatments Compared**	***P-value (2-tailed sig.)***				
GrM vs. GF	2,3,4,5,6,7,8 vs. 9,10,11,12,13,14,15	0.01*	< 0.01*	< 0.01*	ND	0.46
GrM vs. Control-SF	2,3,4,5,6,7,8 vs. 1	0.61	0.03*	0.84	ND	0.52
GrM vs. Control-Wh	2,3,4,5,6,7,8 vs. 16	0.08	0.04*	0.13	ND	0.57
GF vs. Control-SF	9,10,11,12,13,14,15 vs. 1	0.23	< 0.01*	0.07	ND	0.31
GF vs. Control-Wh	9,10,11,12,13,14,15 vs. 16	0.96	0.57	0.91	ND	0.85
GrM intercrops vs. GF intercrops	3,4,5,7 vs. 10,11,12,14	0.21	0.69	0.56	ND	0.14

ND = Not determined
* = Significant at $P < 0.05$ level,
† = Tilled fallow-control,
‡ = Wheat-control,
§ = Field pea + oat 1,2,3 = 50, 100, & 150 plants m^{-2} respectively.

There were no significant differences in soil N between treatments that followed the GrM system and those following the GF system. As well, there were no significant differences in soil N between treatments that followed the GrM regime, nor were there differences in treatments following the GF management system. Treatments following Control-Wh had the least soil N (Table 4-11).

At Delisle, some treatments had more soil N than others. For instance, treatments following the GrM system had significantly higher N than treatments following the GF system. There seemed to have been no trend of increasing or decreasing N with increasing soil depth, although a few treatments showed either trend. However, the plots following the GrM FP_{mono} treatment had over double the amount of N at the 30 to 45-cm depth than at 0- to 15- and 15- to 30-cm depths. Interestingly, plots following monocropped cereals seemed to have N levels decreasing with increasing depth.

At Delisle, plots following GrM FP_{mono} had higher N (43 kg ha^{-1}) at the 0- to 45-cm depth than other plots. Interestingly, plots following intercropped GrM FP+TR had the second highest amount of N (35 kg ha^{-1}) followed by those after FP+O1 (34 kg ha^{-1}) and third were those following the Control-SF (32 kg ha^{-1}) treatment. However, there were no significant differences among these values. Furthermore, plots following the GrM intercrops had significantly more soil N levels than their corresponding GF counterparts.

The GrM versus Control-SF, GrM versus Control-Wh, and GF versus Control-SF at Delisle were all significant at the 15- to 30-cm depth, where the Control-SF had more soil N than the GrM and GF systems and the GrM system had higher soil N than the Control-Wh. However, GF versus Control-Wh was not significant at all soil depths at Delisle (Table 4-11).

4.5 Discussion

4.5.1 Spring soil nitrogen following treatments

One of the objectives of this study was to evaluate the effect of GrM plough-down, GF removal, tilled fallow-control, and wheat-control on available soil N (Table 4-3 and Table 4-4). At Vonda, the GrM regime returned more N to the soil than did the GF system, although absolute amounts were generally very low. This was expected as the GF regime only returned the below-ground biomass whereas the above-ground material was exported through harvesting. These results suggest that green manuring has the ability to increase soil organic matter (SOM) and microbial biomass pools through decomposition of plant materials by soil microbes and subsequent mineralization (Sullivan, 2003). However, the extent of such changes is dependent on management, environmental conditions, and GrM dry matter accumulation (Cherr et al., 2006).

Sullivan (2003) contends that the amount of N from legumes is dependent on legume species, total biomass accumulated, and the percentage of N contained in the plant tissue. Sullivan (2003) further notes that legume growth can be limited by cultural and environmental conditions such as delayed planting date, poor establishment of the stand, and drought, which will in turn reduce the amount of N produced. On the other hand, optimum N production may be encouraged by good stand establishment, optimum soil nutrient levels and soil pH, good nodulation, and adequate soil moisture (Sullivan, 2003). Sullivan's observation is in agreement with results in this study that showed that the FP_{mono} consistently produced significantly higher biomass and accumulated more N than other treatments. Since field pea is traditionally grown on the Canadian prairies, it is a well adapted pulse crop to the cultural and environmental conditions in Saskatchewan.

Sullivan (2003) observed that there is a rapid increase in soil microbes after a young GrM is ploughed down. These microbes quickly multiply to break down the freshly ploughed down plant material. When these microbes undergo decomposition following death, nutrients held within are released and made available to the subsequent crop. Less lignified, lush GrM are richer in N relative to C compared to more lignified crop residues. Thus, it would take longer for soil microbes to break down the more lignified crop materials than it would take for microbes to break down the less lignified materials (Sullivan, 2003). However, if GrM are incorporated later, one benefit would be that more N would be added to the soil.

In this study, it is likely that the lush green GrM top herbage material that was ploughed down was easy for soil microbes to break down. A principal determining factor for soil N availability, regardless of placement of residues in the soil, is the N content or C:N ratio of crops (Ranells and Wagger, 1996). Kuo and Sainju (1998) reported that as N content of plant residue increases or C:N ratio decreases, initial soil N mineralization potential and rate of N mineralization increases, thus making available the N in the residue for plant uptake.

The Control-SF treatment also returned more N to the soil likely due to the fact that weeds that were growing in these plots were tilled under and essentially served as GrM through tillage. One benefit to this system may be that the farmer would gain some income through saving time and effort that is associated with the GrM cropping system. Although moisture levels were not measured, it is possible that in the Control-SF system, there was more moisture in the soil profile at the end of the season as there was no crop that was growing in it throughout the growing season. As well, there was no uptake of N by a crop in this system and there was continual mineralization of SOM throughout the growing season. Other factors that might have contributed to higher N levels in the Control-SF treatments include optimum rainfall (Table 4-2), favourable average temperatures (Table 4-2), and optimum soil N levels, although all the other systems were subjected to the same conditions. However, the down-side to the Control-SF system as compared to the GrM system is that it may not be a sustainable system in the long-term as there are no crops being ploughed down.

At Delisle, soil N results followed a similar trend with those obtained at the Vonda site. Green manure treatments returned more N to the soil than did the GF treatments. Aulakh et al. (2001) observed that N from an incorporated GrM was taken up by the following crop more efficiently than urea N due to the slow release of N associated with mineralization and also due to lower losses of gaseous N. The results in this study are consistent with their findings as the most probable reason for the higher amounts of N in the soil is that the incorporated plant materials were mineralised and made available to the next crop whereas removal of above-ground plant material significantly reduced the mineralization of N following GF treatments compared to GrM treatments.

A study conducted by Fowler et al. (2004) in New Zealand on an established organic farm compared three GrM crops [oat (*Avena sativa*), lupin (*Lupinus angustifolius*), and oat-lupin mix] and a fallow treatment, for their ability to conserve N over winter and their influence on availability of N to a subsequent crop. They concluded that inclusion of GrM crops into a cereal crop rotation effectively reduced N losses associated with leaching over winter and significantly improved supply of N to the subsequent crop as compared to the fallow treatment. They reported N accumulation of 100, 126, and 162 kg N ha^{-1} for oat, oat + lupin, and lupin, respectively before ploughing them down as GrM. Fowler et al. (2004) attributed the lower N amounts associated with monoculture cereal treatments to the net immobilization of N due to high C:N ratios whereas the higher N amounts in wheat treatments following FP_{mono} and field pea-cereal intercrops were as a result of a combination of the addition of N through N_2-fixation and the mineralization of N from the field pea residues resulting from the high concentrations of N and low C:N ratios.

Kuo and Sainju (1998) reported that non-legume cover crops such as cereals are capable of reducing N leaching during wet seasons, whereas legume cover crops improve soil N for subsequent crops. They contend that with cereal-legume intercrops, the objective of reducing N leaching while increasing N availability for the succeeding crop is possible. Although their study was conducted under a humid climate, it is possible that these conditions may be similar to conditions in Saskatchewan during the rainy season. This may explain why the GrM FP_{mono} treatment had more N leached to the 45-cm depth whereas intercrops were intermediate and monocropped cereals exhibited a trend of decreasing N with increasing depth (Table 4-11).

In this study, treatments following GrM FP_{mono} had the highest amounts of N followed by treatments after field pea-cereal intercrops and lastly wheat treatments following monocropped cereals. This phenomenon may be attributed to differences in plant tissue quality between field pea and cereal crops. For instance the field pea was less lignified and therefore easier to break down by microbes than the more lignified and harder to break down oat and triticale. As well, the low C:N ratio of field pea meant that its N content was higher. Kuo and Sainju (1998) noted that as C:N ratio decreases, N content of plant residue increases, initial soil N mineralization potential and rate of N mineralization increases, thus making available the N in the soil for the subsequent crop.

4.5.2 Wheat biomass accumulation at Vonda and Delisle

Benefits to cereal productivity following GrM legume or legume-cereal intercrops have been reported. Fowler et al. (2004) reported that inclusion of GrM crops significantly improved supply of N to the subsequent cereal crop. As well, Evans et al. (1991) and Oikeh et al. (1998) reported yield gains of subsequent cereals ranging from 50 to 80 % more after legume crops than that following cereal-cereal cropping. In this study, this benefit was observed with the accumulation in biomass of the following wheat crop.

Treatments following GrM incorporation accumulated more biomass than those following GF treatments. However, wheat following Control-SF treatments performed well due to a combination of factors. Firstly, nutrients that were initially in the soil were retained, as no crop grew in these plots to take up any nutrients. Secondly, weeds that grew in these plots and took up nutrients from the soil were tilled back and essentially served as GrM when they were tilled back. The ploughed down material was decomposed by soil microbes and the nutrients were likely made available to the following wheat crop. Thirdly, although water conservation was not measured, it is likely that these treatments conserved soil moisture for the succeeding wheat crop. Since the Control-SF system was tilled twice in the growing season, treatments in this system, this may have enhanced soil N availability to the next wheat crop. Dinnes et al. (2002) reported that tillage enhances mineralization processes of crop residues and soil organic N and Al-Kaisi and Licht (2004) reported that tillage increases accumulation of residual soil nitrate.

At both sites, the trend was the same, in that wheat biomass increased from 30 DAP to 72 DAP for most of the treatments at Vonda and from 30 DAP to 86 DAP for most of the treatments at Delisle. This difference may be explained by the fact that there was more available soil N at Delisle than at Vonda (Table 4-4 and Table 4-3, respectively).

Not surprisingly, all wheat following cereals had low productivity, probably because they lacked the legume component which would have been responsible for N_2-

fixation. Due to the small stature of the triticale crop and thus less biomass ploughed down, these treatments would not have a large impact on removing and returning more N to the soil compared to the oat treatments, which had more developed shoots. Thus, the higher oat biomass that was ploughed down may have significantly contributed to availability of N for the subsequent wheat crop. Additionally, monoculture oat treatments may have mineralised more than other cereal crops as they were ploughed down while still less lignified. Mineralization was supported by suitable climatic conditions as well as optimum soil temperature, moisture, and pH favouring dry matter accumulation.

4.5.3 Wheat nitrogen accumulation at Vonda and Delisle

At both sites, N accumulation increased for the first three to four samplings as the plants were actively growing and their vigorous root systems were extracting N from the soil. Of interest in these experiments were the Control-SF treatments, which had the highest amounts of N in the following wheat crop. Many studies have shown that tillage enhances mineralization of crop residues and soil organic N (Dinnes et al., 2002) as well as increases accumulation of residual soil nitrate (Al-Kaisi and Licht, 2004).

Wheat following the GrM FP_{mono} accumulated higher N amounts because of the higher N content in the FP_{mono} that was returned into the soil. These results are consistent with similar past experiments. Campbell et al. (1991) observed that inclusion of legumes as GrM or hay crop in rotation increased N amounts especially in the 7.5- to 15-cm soil depth. As well, treatments following GrM intercrops accumulated significantly higher N than those following GF intercrops. The GrM treatments were ploughed down and therefore returned nutrients into the soil unlike the harvested GF treatments.

4.5.4 Wheat grain yield at Vonda and Delisle

The benefits of legumes, fallowing, and intercropping were observed at both sites in terms of subsequent wheat grain productivity. These results are supported by previous studies. For instance, Wivstad (1997) demonstrated that subsequent spring wheat grain yield was up to 2500 kg ha^{-1} greater after whole-season GrM Persian clover (*Trifolium resupinatum* L.) than spring wheat following oat (*Avena sativa* L.). Milkha et al. (2001) noted that incorporating GrM crops increased SOM while maintaining high grain yields of the subsequent cereal crop. Peoples and Herridge (1990) reported cereal grain yields ranging from 16 to 353% following tropical legume crops compared to cereal-cereal monoculture grain yields. Control-SF essentially served as GrM, as well as conserving soil moisture and nutrients, thus wheat grain productivity in plots following this treatment was higher.

Furthermore, wheat grain productivity following intercrops was significantly higher than their monoculture cereal counterparts thus providing evidence that N_2-fixation by the legume component of the intercrop was beneficial to this association. However, even for the harvested GF treatments, wheat grain yield was highest in treatments following the GF FP_{mono} (Table 4-9). Total grain N followed a similar trend as that of the grain biomass largely due to the fact that total N is a function of %N and biomass of each component crop.

At Delisle, the trend in grain yield and N was similar to that at Vonda. There were no differences in wheat following GrM FP_{mono} (1290 kg ha^{-1}) and wheatfollowing the Control-SF (1353 kg ha^{-1}) treatments for grain yield and 40 kg ha^{-1} and 41 kg ha^{-1} for grain N, respectively (Table 4-10). Surprisingly, treatments following GF FP+O1 (1290 kg ha^{-1}) produced a higher grain biomass than wheat following GrM FP+O1 (1103 kg ha^{-1}). This may have been caused by the higher initial concentration of available soil nutrients at this site than at Vonda. Grain productivity at this site was comparatively less than that obtained at Vonda, despite the fact that the Delisle site contained higher initial soil N concentration than Vonda.

Wheat grain N accumulation at Delisle also followed a similar trend to the grain biomass as described above. According to Strong et al. (1986b), wheat grain N was higher in legume-wheat rotations as opposed to cereal-wheat or oilseed-wheat rotations. Many other studies (Evans et al., 1991; Chalk et al., 1993) have acknowledged the fact that N is a key factor in yield responses of cereals grown after legumes, compared to cereal yields following non-legume crops.

4.5.5 Soil nitrogen levels following final wheat harvest at Vonda and Delisle

There were no significant differences among all treatments at the 0- to 15-cm soil depth at Vonda. At the end of the second year, plants had depleted soil N at this upper horizon. However, it is possible that if other lower soil horizons had been sampled, there may have been differences among treatments as some of the N may have leached to these lower horizons.

On the other hand, at Delisle, significant differences were observed at all three soil depths between treatments following the GrM and GF regimes with the GrM system clearly exhibiting higher soil inorganic N than the GF system. Treatments following GrM intercrops retained more N than those following the GF regime at all three soil depths. This observation may be explained by the fact that there was a combination of higher initial soil N and subsequently, N made available to the subsequent wheat crop from mineralization of the ploughed down plant material. Wheat following FP_{mono} treatments had the highest amount of N, suggesting that field pea as a legume is advantageous in legume-cereal crop rotations.

Treatments following GrM FP+O1, FP+TR, and FP+O3, had higher N amounts than GrM O_{mono} and TR_{mono} suggesting that intercropping may be a better cropping practice than monocropping cereals or other non-legume crops. In particular, treatments following the GrM FP+O1 had the highest amount of N among all intercrops. This shows that this treatment was easily broken down by microbes and mineralized to release the N into the soil. Treatments following the GrM FP+ TR also did well because of the field pea component, which had a lower C:N (11:1) and high N concentrations. As well, the field pea may have been less lignified plant material at the time of ploughing down, and hence was easy to break down and mineralize. Other environmental factors such as enough soil moisture and optimum soil temperature may have played a role at this site.

On the other hand, there were no noticeable differences in all treatments in soil N levels at Vonda. This may be a result of lower available N levels at this site. Thus, whatever may have been stored in the soil during the first cycle was used up by the subsequent wheat crop.

4.6 Recommendations and Conclusion

Wheat following FP_{mono} and Control-SF yielded the most biomass, took up the most N, and in most cases retained the most soil N after the final wheat grain harvest. In the Control-SF treatments, mineralization of plant materials and humus by soil microbes aided these treatments to achieve higher yields than most of the other treatments. Whereas wheat yields were consistently higher following GrM treatments than those following the GF treatments at Vonda, this was not always the case at the Delisle site.

This study demonstrated that wheat grain yield in the second season was highest in treatments following the GrM management system and particularly those treatments after FP_{mono} and Control-SF, and intercrops. Even under the GF system, treatments following field pea out-performed their counterparts where field pea was not a component crop. In terms of improving the soil nutrient status of the subsequent crop and as a long-term sustainability option, the GF system may not be a sustainable option that organic farmers can adopt as nutrients are exported out of the field through harvesting. Furthermore, the FP_{mono} proved to be the most productive of all the crops dealt with in this study.

For organic farmers, the traditional green manuring method may still be the best farming practice, especially for those farms in similar weather or climatic conditions and soil types as the ones under which this research was conducted. As well, inclusion of legumes alone or intercropped is still a better option in rotation with cereals than cereal-cereal rotations. Since the main objective of this study was to evaluate the productivity of GrM and GF options in organic cropping systems, the results of this study can only support the GrM system especially including monoculture legume in rotation.

Although the rationale behind including triticale in this study was due to its allellopathic capabilities and thus was thought to help suppress weeds, it did not perform any better at suppressing weeds than other crops in this study. In fact, due to its small stature, it was suppressed by weeds whereas other cereals such as oat and wheat were better at suppressing weeds than triticale. In terms of biomass and N accumulation, triticale performed poorly compared to other cereals. Therefore, it may be worthwhile to consider the growth pattern, ability to compete, and overall productivity of a particular crop before including such a crop in a rotation or legume-cereal intercrop.

5 GENERAL DISCUSSION

In recent years, western Canada has seen considerable growth in organic production. This growth is due to heightened environmental awareness, reduced input costs, diversification of market opportunities, and food safety concerns. On the prairies, organic farming often includes the use of annual GrM crops, which are ploughed under to add nutrients to the soil for subsequent crops. Our study was initiated to examine whether it was worthwhile to consider GF as an alternative to GrM. We thought that GF might provide some income to farmers and still be equally good in terms of returning nutrients to the soil for the following crop.

This study was established as a two-year field experiment to compare productivity of the GrM and GF regimes. Tilled fallow and wheat management systems served as controls. A randomized complete block design was used. The experiment consisted of 16 treatments and 4 replicates in which field pea, oat, and triticale were grown alone or in combination and managed either as GrM or GF. The two controls were included because, firstly, the tilled fallow system has been used and proven to benefit the soil and subsequent crops in terms of nutrients (Biederbeck et al., 1994) whereas cereal stubble typically minimizes net mineralization of soil N (Campbell et al., 1991).

Specific objectives of this study were to: i) compare biomass and N yield in GrM and GF management systems; ii) investigate whether increasing cereal density enhances N_2-fixation in the intercropped legume; iii) evaluate soil N levels following GrM and GF treatments; and iv) compare productivity of the cereal crop following GrM, GF, and controls.

This study showed that there are benefits of intercropping cereals with legumes as intercropped cereals produced more biomass and accumulated more N than their monocropped cereals. This may be supported by the fact that there is a complementary effect between the legume and cereal components of an intercrop (N-sparing), where the legume derives its N from N_2-fixation and the cereal gets its N from the soil. Benefits of intercropping are well documented (Corre-Hellou et al., 2006; Hauggaard-Nielsen et al., 2007). By intercropping legumes with cereals, it is assumed that the legume component fixes N from the atmosphere, whereas the cereal derives its N from the soil. Fujita et al.

(1992) noted that where fertilizer N is limited as in organic production, biological nitrogen fixation (BNF) is the main source of N. Compared to monocropping, intercropping enhances the use of available resources, and increases yield and stability of crops (Corre-Hellou et al., 2006; Ofori and Stern, 1987; Hauggaard-Nielsen et al., 2007). Whereas many studies have reported that the fixed N is available to both current and subsequent cereal crops (Fujita et al., 1992; Pal and Shehu, 2001; Pappa et al., 2006), other studies have not observed N transfer from legume to cereal in the current year (Izaurralde et al., 1992; Ofori and Stern, 1987). We asked whether intercropping a legume and a cereal would increase crop productivity in the current and subsequent year and whether increasing cereal density in a pea-cereal intercrop would stimulate N_2-fixation.

In the treatment year (year 1), both biomass productivity and N accumulation was consistently higher in GF treatments than in GrM, with some GF treatments achieving more than double the biomass and N accumulation than their GrM counterparts. Among all treatments, the FP_{mono} under the GF system achieved the highest biomass and N accumulation compared to all other treatments.

These results are consistent with other similar past studies that have reported that legume monocrops accumulate more N than their intercrops. For instance, Andersen et al. (2007) reported significant differences in shoot dry weight and N concentrations between monocropped pea and pea-barley and pea-barley-rape intercrops. They observed that the monocropped pea produced the largest amount of shoot biomass and accumulated the most N from the middle to the end of the growing season. Their monocropped pea produced about 6000 kg ha^{-1} shoot dry weight compared to pea-barley and pea-barley-rape intercrops, which produced approximately 5000 kg ha^{-1} of their shoot dry weight for each intercrop. In another study, N accumulation in above-ground herbage was 100, 126, and 162 kg N ha^{-1} for oat (*Avena sativa*), oat-lupin (*Lupinus angustifolius*), and lupin, respectively (Fowler et al., 2004). In this study, the GF monocropped field pea produced biomass of 6095 kg ha^{-1} and 5210 kg ha^{-1} and accumulated N of 161 kg N ha^{-1} and 145 kg N ha^{-1} at Vonda and Delisle, respectively.

The higher productivity of the GF regime is not surprising considering the fact that it was allowed to grow for two weeks after the GrM had been ploughed down.

However, the extra two weeks of growth for the GF system may have come at a cost as this meant that more nutrients were taken up by these crops and exported out of the soil resulting in significant lower N levels in the soil and lower wheat yield in the following year. These results may suggest that timing of incorporation of GrM plant material is critical in order to achieve maximum or optimal plant biomass, N accumulation, and N_2-fixation while conserving soil moisture for the subsequent crop. For instance, if ploughed down early, crops will not maximize N_2-fixation, but if ploughed down late the current crop could deplete soil moisture for the next crop (AAFRD, 1993; SAF, 2006).

In the wheat year (year 2), the benefits of GrM to the following wheat crop were evident in terms of soil nutrients and wheat biomass and N accumulation. Soil inorganic N levels in plots following GrM treatments were comparable to those of the Control-SF system and significantly higher than in plots following the GF system. In fact, plots following GrM FP_{mono} had higher soil inorganic N than the Control-SF system, which indicates that this treatment supplied more N than was released by net mineralization alone.

The higher soil inorganic N in plots following GrM treatments was further observed in wheat biomass and N accumulation, which were significantly higher than wheat following GF treatments and comparable to wheat following the Control-SF system. The fact that wheat following GrM FP_{mono} was comparable to wheat following the Control-SF system is evidence that a GrM system may be an option to consider by organic farmers because, unlike the Control-SF system which tends to be associated with soil erosion (Campbell et al., 1991), the GrM system prevents soil erosion as plants serve as cover crops before ploughing them down (Sullivan, 2003). The GrM FP_{mono} may be superior to traditional summer fallow for organic farmers because of the potential of this system to prevent soil erosion. Furthermore, unlike the Control-SF system, the GrM system has a long-term benefit to the soil and to subsequent crops as it adds nutrients to the soil through incorporation. Wheat yield responses following GrM plough-down were much higher compared to wheat grown following GF harvesting. Differences in wheat biomass and N accumulation were observed in the range of 30% to 60% between wheat following the two systems.

The incorporation of GrM crops ensured decomposition of the ploughed down material and subsequent mineralization of the material by soil microbes. For instance, Sullivan (2003) observed that there is a rapid increase in soil microbes after a young GrM (legume or cereal) is ploughed down. Microbes quickly multiply to break down the freshly ploughed down plant material. When these microbes finally break down, nutrients held within the plant materials are released (mineralized) and made available to the subsequent crop (Sullivan, 2003).

Wheat growth following intercrops was intermediate between monocropped field pea and monocropped cereals. Our results are consistent with other similar studies. For instance, a study conducted by Fowler et al. (2004) in New Zealand on an established organic farm compared three GrM crops (oat, lupin, and oat-lupin mix) and a fallow treatment, for their ability to conserve N over winter and influence availability of N to a subsequent crop. They observed N accumulation in the plant material of 100, 126, and 162 kg N ha^{-1} for oat, oat + lupin, and lupin, respectively before ploughing them down as GrM. Fowler et al. (2004) attributed the lower N amounts in the soil associated with monoculture cereal treatments to the net immobilization of N due to high C:N ratios whereas the higher N amounts in wheat treatments following monocropped field pea and pea-cereal intercrops were the result of a combination of the addition of N through N_2-fixation and the mineralization of N from the field pea residues resulting from the high concentrations of N and low C:N ratios. The fact that monocropped field pea had a lower C:N ratio suggests that this treatment was easily mineralized compared to monocropped cereals, which had higher C:N ratios suggesting that these treatments were slower to mineralize (Sullivan, 2003). However, it is worth noting that the higher N accumulation in wheat following the GrM system is a result of N-uptake from the soil and N_2-fixation by the legume crop.

This study did not find any direct transfer of N from the legume to the cereal component in the current year. The higher biomass and N accumulation in intercrops may have been largely due to the N-sparing effect between intercrops. However, the benefits of intercropping to the soil and the subsequent wheat crop were noticed in plots that had GrM treatments. In the treatment year, intercropped biomass and N accumulation was intermediate between monocropped field pea and monocropped cereals. Results of this study showed that increasing cereal density did not increase N_2-fixation. However, the higher biomass in the intercropped cereals compared to their monoculture counterparts, may have been due to the complimentary use of soil inorganic and atmospheric N by the intercropped components, thus resulting in reduced competition (N-sparring) for inorganic N (Jensen, 1996). Since this study only examined two sites, this may warrant further research at difference sites before any conclusive recommendations can be made regarding optimal cereal density in an intercrop. In this study, intercropped field pea fixed an average of 71% and 96%, or 49 kg N ha^{-1} and 130 kg N ha^{-1}, respectively, under GrM and GF systems, while monocropped field pea fixed 64% and 78% (or 51 and 111 kg ha^{-1}) under the same management systems, respectively. Increasing cereal density in an intercrop is thought to stimulate N_2-fixation (Evers, 2006). Corre-Hellou et al. (2006) observed that the intensity of competition in a legume-cereal intercrop is dependent on the supply of soil N and the densities of cereal plants.

Jensen (1996) observed that more of the N in the intercropped pea was derived from N_2-fixation than in the monocropped pea, averaging 82% and 62%, respectively. Jensen (1996) contended that the advantage in a pea-barley intercrop was mainly due to the complimentary use of soil inorganic and atmospheric N sources by the intercropped components, which resulted in reduced competition for inorganic N. Izaurralde et al. (1991) found that on average the proportion of N derived from air by pea intercrops was 39% higher than that derived by the single pea crop. They attributed these yield advantages by intercropping to the mutual complimentary effects of individual crops including better use of available resources such as light, water, and nutrients (Izaurralde et al., 1991). These results are consistent with results obtained in this study. For instance, the proportion of fixed N as a percentage of total N was 62% for GrM monocropped field pea and 76% for GF monocropped field pea compared to an average of 65% for GrM intercrops and 93% for GF intercrops.

This study also demonstrated that choosing a suitable cereal crop is an important step in intercropping. Triticale was tested because it is thought that when used as a cover crop it has allelopathic properties that would create unfavourable conditions for weed germination and establishment (Khanh et al., 2005). In their study, Khanh et al. (2005) observed that allelopathic crops, when used as cover crops, mulch, smother crop, green manure, or grown in rotational sequences, were helpful in reducing noxious weeds and plant pathogens and improved soil quality and crop yield. In this experiment, triticale was relatively slow growing and remained relatively small, which provided little competition for actively growing weeds compared to other cereals (oat and wheat), which grew relatively bigger than triticale. It may be that other factors present were antagonist to the allelopathic abilities of triticale.

Finally, further investigations are required to establish the optimal cereal density in intercropping by examining more field sites in Saskatchewan and across the prairies before recommendations are made to organic farmers. Further research also is required in establishing which cereal crops possess allelopathic potential to suppress weeds from germinating and getting established in the fields. This is particularly important to organic farmers who must rely on means of weed suppression other than herbicides. Further exploration may include assessing the effects of the P-solubilising inoculants, the efficiency of the root systems of field pea and cereals in extracting N and other nutrients, and any mycorrhizal associations involved among the crops under study.

Following wheat harvest in the second year, soil inorganic N levels had considerably declined compared to N levels before seeding wheat. There were no differences in soil inorganic N in all plots at Vonda. However, significant differences were observed in soil inorganic N between plots where wheat was grown following GrM and GF systems. Plots that originally had GrM treatments had higher soil inorganic N than plots that initially had GF treatments. These results suggest that there are benefits to the soil by using the GrM approach for organic farming.

In this study, the GF system showed that farmers intending to adopt this system for haying can benefit from the higher biomass and N accumulation of GF crops in the short-term. However, as discussed earlier, this system may not be sustainable in the long-term. On the other hand, the GrM system, although less productive in the first year, was beneficial to both the soil and subsequent wheat crop, thus more beneficial in the long-term than the GF system. The Control-SF system was also beneficial to the soil and wheat crop in the following year, but may not have long-term benefits as nutrients are not returned. The Control-Wh system performed poorly in both years and may not be a good replacement for any of the systems above.

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7 APPENDICES

Appendix A

Table A-1 Randomised complete block design of the first cycle treatments including the block, plot, and treatment numbers at the Vonda site in 2004. Each plot measured 4 by 6 m

Block 1		Block 2		Block 3		Block 4	
Plot	**Treat.**	Plot	**Treat.**	Plot	**Treat.**	Plot	**Treat.**
101	**11**	201	**7**	301	**10**	401	**13**
102	**2**	202	**3**	302	**4**	402	**16**
103	**1**	203	**5**	303	**9**	403	**1**
104	**12**	204	**14**	304	**3**	404	**12**
105	**16**	205	**15**	305	**16**	405	**7**
106	**8**	206	**4**	306	**7**	406	**9**
107	**9**	207	**12**	307	**2**	407	**5**
108	**5**	208	**13**	308	**13**	408	**11**
109	**3**	209	**2**	309	**14**	409	**15**
110	**7**	210	**6**	310	**1**	410	**3**
111	**14**	211	**1**	311	**8**	411	**14**
112	**13**	212	**10**	312	**11**	412	**4**
113	**15**	213	**11**	313	**15**	413	**8**
114	**10**	214	**16**	314	**12**	414	**6**
115	**4**	215	**9**	315	**6**	415	**2**
116	**6**	216	**8**	316	**5**	416	**10**

Table A-2 Treatment names and plots numbers under GrM, GF, Wheat, and Fallow management systems and following wheat crop at Vonda in 2004 and 2005

Treat.	Year 1	Year 2	Plots
1	Fallow-control	Wheat	103, 211, 310, 403
2	Field pea (GrM)	Wheat	102, 209, 307, 415
3	Field pea + Oat 1 (GrM)	Wheat	109, 202, 304, 410
4	Field pea + Oat 2 (GrM)	Wheat	115, 206, 302, 412
5	Field pea + Oat 3 (GrM)	Wheat	108, 203, 316, 407
6	Oat (GrM)	Wheat	116, 210, 315, 414
7	Field pea + Triticale (GrM (GM) (((GM)	Wheat	110, 201, 306, 405
8	Triticale (GrM)	Wheat	106, 216, 311, 413
9	Field pea (GF)	Wheat	107, 215, 303, 406
10	Field pea + Oat 1 (GF)	Wheat	114, 212, 301, 416
11	Field pea + Oat 2 (GF)	Wheat	101, 213, 312, 408
12	Field pea + Oat 3 (GF)	Wheat	104, 207, 314, 404
13	Oat (GF)	Wheat	112, 208, 308, 401
14	Field pea + Triticale (GF)	Wheat	111, 204, 309, 411
15	Triticale (GF)	Wheat	113, 205, 313, 409
16	Wheat-control	Wheat	105, 214, 305, 402

Table A-3 Randomised complete block design of the first cycle treatments including the block, plot, and treatment numbers at the Delisle site in 2005. Each plot measured 4 by 6 m

Block 1		**Block 2**		**Block 3**		**Block 4**	
Plot	**Treat.**	Plot	**Treat.**	Plot	**Treat.**	Plot	**Treat.**
501	**13**	601	**10**	701	**15**	801	**1**
502	**4**	602	**6**	702	**2**	802	**16**
503	**3**	603	**8**	703	**7**	803	**5**
504	**14**	604	**1**	704	**5**	804	**4**
505	**2**	605	**9**	705	**14**	805	**11**
506	**10**	606	**7**	706	**1**	806	**13**
507	**11**	607	**15**	707	**16**	807	**9**
508	**7**	608	**16**	708	**11**	808	**15**
509	**5**	609	**13**	709	**12**	809	**3**
510	**9**	610	**2**	710	**8**	810	**7**
511	**16**	611	**4**	711	**6**	811	**2**
512	**15**	612	**5**	712	**9**	812	**8**
513	**1**	613	**14**	713	**13**	813	**12**
514	**12**	614	**3**	714	**10**	814	**14**
515	**6**	615	**12**	715	**4**	815	**6**
516	**8**	616	**11**	716	**3**	816	**10**

Table A-4 Treatment names and plot numbers under GrM, GF, Wheat, and Fallow management systems and following wheat crop at Delisle in 2005 and 2006

Treat.	Year 1	Year 2	Plots
1	Fallow-control	Wheat	513, 604, 706, 801
2	Field pea (GrM)	Wheat	505, 610, 702, 811
3	Field pea + Oat 1 (GrM)	Wheat	503, 614, 716, 809
4	Field pea + Oat 2 (GrM)	Wheat	502, 611, 715, 804
5	Field pea + Oat 3 (GrM)	Wheat	509, 612, 704, 803
6	Oat (GrM)	Wheat	515, 602, 711, 815
7	Field pea + Triticale (GrM)	Wheat	508, 606, 703, 810
8	Triticale (GrM)	Wheat	516, 603, 710, 812
9	Field pea (GF)	Wheat	510, 605, 712, 807
10	Field pea + Oat 1 (GF)	Wheat	506, 601, 714, 816
11	Field pea + Oat 2 (GF)	Wheat	507, 616, 708, 805
12	Field pea + Oat 3 (GF)	Wheat	514, 615, 709, 813
13	Oat (GF)	Wheat	501, 609, 713, 806
14	Field pea + Triticale (GF)	Wheat	504, 613, 705, 814
15	Triticale (GF)	Wheat	512, 607, 701, 808
16	Wheat-control	Wheat	511, 608, 707, 802

Appendix B

Table B-1 Physical and chemical characteristics of soil following GrM and GF treatments at Vonda in 2005

	Soil Depth (cm)								
	0 – 15	**15 – 30**	**30 – 45**	**0 – 15**	**15 – 30**	**30 – 45**	**0 – 15**	**15 – 30**	**30 – 45**
Treatment ID	**MC (%)**			**pH**			**EC (mS cm^{-1})**		
Fallow-control	12	15	18	7.4	7.7	7.8	0.1	0.1	0.2
Wheat-control	12	14	14	7.5	7.5	7.7	0.1	0.1	0.1
Green Manure (GrM)									
Field pea	11	13	15	7.3	7.4	7.5	0.1	0.1	0.1
Field pea + oat 1	16	14	15	7.4	7.6	7.8	0.2	0.6	0.7
Field pea + oat 2	11	15	13	7.3	7.7	7.5	0.1	0.1	0.1
Field pea + oat 3	12	15	13	7.2	7.5	7.6	0.2	0.6	0.9
Oat	12	12	14	7.2	7.4	7.6	0.1	0.4	0.6
Field pea + Triticale	13	15	17	7.2	7.5	7.8	0.5	0.7	0.7
Triticale	12	16	16	7.2	7.6	7.4	0.2	0.1	0.6
Green Feed (GF)									
Field pea	13	14	13	7.5	7.8	7.8	0.2	0.5	0.6
Field pea + oat 1	12	16	17	7.6	7.7	7.9	0.1	0.2	0.8
Field pea + oat 2	12	15	15	7.0	7.2	7.4	0.1	0.2	0.3
Field pea + oat 3	11	13	18	7.1	7.7	7.9	0.1	0.2	0.3
Oat	12	15	17	7.4	7.5	7.8	0.1	0.3	0.6
Field pea + Triticale	13	14	14	7.5	7.5	7.7	0.2	0.4	0.9
Triticale	12	15	15	6.9	7.2	7.7	0.1	0.2	0.2

Oat 1, 2, 3 = 50, 100, & 150 plants m^{-2} respectively.

Table B-2 Physical and chemical characteristics of soil after GrM and GF treatments at Delisle in 2006

	Soil Depth (cm)							
	0 - 15	**0 - 15**	**15 - 30**	**30 - 45**	**0 - 15**	**15 - 30**	**30 - 45**	**0 - 15**
Treatment ID	**MC (%)**	**pH**			**EC (mS cm^{-1})**			**BD (g cm^{-3})**
Fallow-control	18	6.0	6.8	7.4	0.2	0.2	0.7	1.4
Wheat-control	21	6.1	6.9	7.5	0.2	0.2	1.2	1.4
Green Manure (GrM)								
Field pea	18	6.1	7.0	7.4	0.2	0.3	0.7	1.4
Field pea + oat 1	20	6.4	7.1	7.6	0.2	0.2	1.2	1.5
Field pea + oat 2	20	6.3	7.1	7.5	0.2	0.2	0.6	1.4
Field pea + oat 3	19	6.2	7.2	7.5	0.2	0.3	1.4	1.4
Oat	18	6.3	7.3	7.6	0.2	0.6	2.3	1.5
Field pea + Triticale	19	6.3	7.4	7.7	0.3	0.4	1.0	1.3
Triticale	17	6.3	7.1	7.6	0.2	1.1	2.2	1.4
Green Feed (GF)								
Field pea	18	6.1	6.8	7.5	0.2	0.3	1.0	1.4
Field pea + oat 1	19	6.6	7.4	7.8	0.2	0.6	1.6	1.4
Field pea + oat 2	18	6.4	7.2	7.6	0.2	0.4	1.6	1.3
Field pea + oat 3	19	6.1	7.3	7.8	0.2	0.5	2.5	1.5
Oat	18	6.1	6.9	7.6	0.1	0.3	1.6	1.4
Field pea + Triticale	17	6.4	7.3	7.7	0.2	0.3	1.7	1.3
Triticale	16	6.0	6.9	7.4	0.1	0.2	1.1	1.3

Oat 1, 2, 3 = 50, 100, & 150 plants m^{-2} respectively.

Appendix C

Figure C-1 Wheat plots following GrM and GF treatments at Vonda in 2005. Higher biomass and N yield were achieved in treatments which had been previously cropped with monoculture field pea or intercrops.

Figure C-2 Wheat plots following GrM and GF treatments at Delisle in 2006. Higher biomass and N yield were achieved in treatments which had been previously cropped with monoculture field pea or intercrops

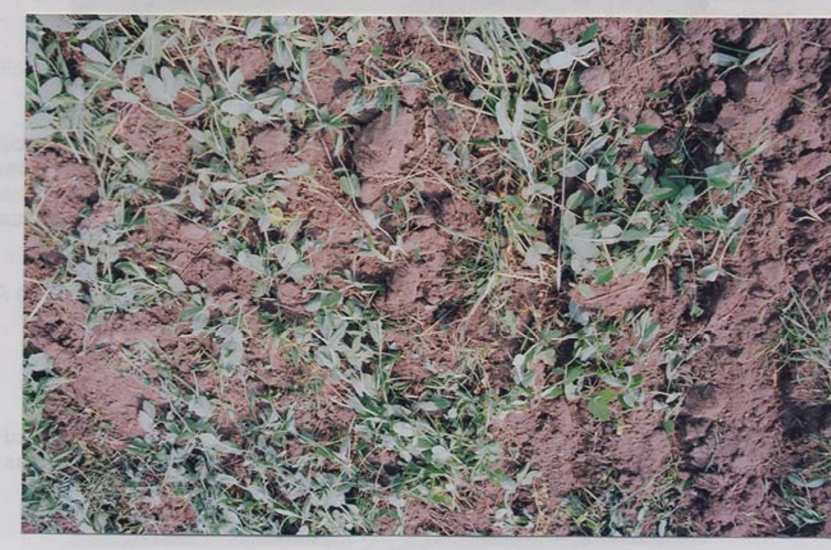

Figure C-3 Pea-oat intercrop (above) and green manure (GrM) plough-down (below) at Vonda in 2004