Optimizing the Nitrogen Supply of Prairie Organic Agriculture with Green Manures and Grazing

BY

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ABSTRACT

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There is a need to design green manure systems that can supply optimum Nitrogen (N) to cash crops and that are compatible with intensive annual crop production. Grazing and no-till management in organic systems have been recently proposed tools to improve nutrient cycling and sustainability. From 2008 to 2012, a series of field experiments were conducted to *i)* identify green manure species and *ii)* green manure management options to maximize N benefit to following cash crops and explore the opportunities to reduce tillage during the green manure phase of an organic rotation. A total of four green manure systems (double-cropped green manures, relay-cropped green manures, full season green manures, and catch crops after grazed full season green manures), three green manure management options (soil incorporation, grazing and no-till), and 10 green manure species, as well as, three green manure mixtures were tested. Among the relay and double crops tested, relay-cropped red clover (*Trifolium pratense*) and double-cropped pea were the greatest biomass producers and N suppliers. Double-cropped pea (*Pisum sativum* cv. 40-10) and relay-cropped red clover produced around 900 kg ha^{-1} and 2000 kg ha^{-1} of dry matter biomass respectively. Overall, relay crops were more productive than the double crops. The greatest biomass producing full season green manures were hairy vetch (*Vicia villosa* L.), pea/oat (*Avena sativa* cv. Leggett) and sweet clover (*Mellilotus officinalis* cv. Norgold). Pea/oat and hairy vetch were the most weed competitive species and on average contained less than 15% weed biomass. When averaged across three years, both green manure types produced around 5000 kg ha^{-1} of biomass. Among all the systems and managements tested, N availability was greatest when full season green manures were grazed. On average grazing increased soil NO_3-N by 25% compared to soil incorporation using tillage. Among grazed species, pea/oat mix and hairy vetch green manures resulted in the greatest amount of soil available NO_3-N. Higher availability of N after grazing of green manures did not increase wheat or fall rye yields compared to soil incorporation. However, grazing also did not decrease the productivity of two following grain crops grown after grazing of green manures. Therefore, in addition to the single benefit of soil fertility, an additional benefit from green manure was potential livestock productivity. The lowest N availability was observed when low green manure biomass was combined with no-till, such as in the case of double crop systems that resulted in low biomass productivity. The higher biomass production by clovers and pea in relay and double crop systems were effective at offsetting reduced tillage-induced N immobilization. Catch crops after grazing green manures, regardless of the species, significantly reduced N leaching risk compared to no catch crop treatment, but also reduced wheat productivity the following year. Catch crop biomass productivity and N uptake, soil NO_3-N, and wheat productivity were similar in direct seeded and conventionally seeded plots. Grazing may be an effective tool in reducing tillage in organic agriculture because of its ability to accelerate the N mineralization from catch crop biomass. This study was the first study to use grazing as a management tool for green manures in organic systems. Results provide strong evidence that green manures,

especially when grazed, can be effective nitrogen suppliers in organic grain-based rotations.

FOREWARD

Agriculture, Ecosystems and Environment Journal format was used for the preparation of the manuscripts.

1. INTRODUCTION

Despite the decades of agricultural research and development industrial society still does not have a firm handle on the nitrogen cycle. We learned how to break the strong triple bond of atmospheric N_2 (i.e. Haber-Bosch and biological N fixation) and create reactive N that can be used in agroecosystems. Hence, in the last century, the amount of reactive N entering the nitrogen cycle and biosphere was doubled (Smil, 1999). However, management of N has not been optimized and 50% of the reactive N that is applied to agroecosystems is lost as leachates and gases (Galloway et al., 2004). Such losses not only create environmental problems, but also hinder productivity of agriculture.

Although inefficiencies and losses of N are prevalent in both synthetic-N based and legume-based systems (Stopes et al., 2002), acquiring N from legumes is regarded as more sustainable (Drinkwater et al., 1998; Crews and People, 2004). In spite of this, reliance on legume-based N has dropped to less than 20% of all N entering agroecosystems (Smil, 1999). Tonitto et al. (2006) argued that this resulted from the commonly held perceptions that 1) a legume green manure must be grown for a full year, thus reducing the number of cash crop cycles, (2) legume management incurs regular ‘opportunity costs’ such as the inability to plant a cash crop due to the timing of green manure incorporation, and (3) legumes cannot provide adequate N for cash crop growth.

A number of management techniques have been proposed to deal with the perceptions outlined by Tonitto et al. (2006). The issue of sparing the whole growing season for green manures may be resolved by growing legumes as double and relay crops (Thiessen Martens et al., 2001a; Blackshaw et al., 2010a). Double and relay cropping have not been tested under organic management in the northern Great Plains. Under conventional management in Iowa, fertilizer replacement value (FRV) of relay-cropped red clover (*Trifolium pratense*) for corn ranged from 87 to 184 kg N ha^{-1} (Liebman et al., 2012). In Manitoba, Thiessen Martens et al. (2005) established the FRV for an oat (*Avena sativa*) crop from relay cropped alfalfa (*Medicago sativa*, 36 kg N ha^{-1}) and red clover (*Trifolium pratense*, 25 kg N ha^{-1}), as well as for double-cropped chickling vetch (*Lathyrus sativus*, 36 kg N ha^{-1}) and lentil (*Lens culinaris*, 31 kg N ha^{-1}). The determining factor for success of organic double and relay cropping systems in colder northern regions will be the potential biomass and N production given the short growing season.

Grazing green manure legumes has been proposed as a strategy to extract immediate economic value (i.e. animal live weight gain or other productivity) from green manure biomass and also accelerate nutrient cycling (Russelle et al., 2007; Thiessen Martens and Entz, 2011). Grazing green manures may address many of the problems attributed to the green manure phase of the rotations. For instance, utilizing the green manure biomass for animal productivity provides a partial solution to income loss as a result of no cash crop production. Also grazing green manure biomass may prepare the land for seeding and create opportunity for other crops (i.e. catch crops). Most importantly, rumen digestion of green manure biomass may increase N-supplying power of green manure residue.

A recurring theme in green manure research is that the amount of N in green manure biomass appears to be sufficient for successful cash crop production but yields in organic or legume-based systems are generally lower than conventional systems (Peoples et al., 1995; Berry et al., 2002). Tonitto et al. (2006) found that at least 50% of the studies included in their meta-analysis reported green manure biomass N accumulation values between 50-150 kg N ha^{-1}, while the in the rest of the studies legume N inputs ranged from 8 to 350 kg ha^{-1}. Biomass nitrogen accumulation values by annual green manures in the Canadian prairies range from 25 to 126 kg N ha^{-1} (Biederbeck et al., 1996; Ross et al., 2009; Vaisman et al., 2011). If conventional crop yields are to be taken as a target, cash crop yields in legume-based systems can match conventional yields when legume-based systems provide at least 110 kg N ha^{-1}, which was possible in 55% of the studies reviewed in Tonitto et al. (2006).

Two issues have been identified with the N supply in legume-based systems. The first is the large variability in the legume N supply reported by studies. Addressing this issue requires identification of legume species with high N supplying capacity. The second concern is that even when there appears to be enough legume N (i.e. >110 kg ha^{-1}), the cash crop does not respond to available N. Asynchrony between the N mineralization from green manure biomass and the cash crop demand is one of the reasons for lower crop productivity in legume-based systems (Berry et al., 2002; Crews and Peoples, 2005). If N is released quickly from green manure biomass, it may be lost to the environment before it is taken up by cash crops. On the other hand, if N is released at a rate slower than crop demand, productivity of cash crops is compromised. Catch crops, sown when excess N is present, have shown to be effective tools for capturing surplus N and releasing it to subserquent crops, thereby addressing N loss when N is released quickly (Doltra and Olesen, 2013). Grazing of green manures, on the other hand, can be used as a management technique to accelerate N availability. Clearly there is a need to design green manure management systems that can meet the cash crop N demands and are in synchrony with intensive annual crop production (Cherr et al., 2006). Such systems would improve yields, diversity and nutrient use efficiency.

After total N supply contributed by legume green manure biomass, tillage and green manure residue management are the greatest determinants of green manure N fate (Drinkwater et al., 2000; Vaisman et al., 2011). In organic agriculture, tillage intensity is often greatest during the green manure phase of the rotation. Incorporating green manure biomass into the soil increases N mineralization rates (Vaisman et al., 2011), controls weeds, and prepares fields for cash crop seeding (Peigne et al., 2007). On the other hand, excessive tillage causes soil erosion, reduces soil organic matter content and negatively affects soil health (Liebig et al., 2004; Montgomery, 2007). Drinkwater et al. (2000) argue that combining reduced tillage practices and use of green manures would solve many of the problems associated with each of these practices when used alone. Past research has focused on alternatives to intensive tillage for green manure management. Examples include mulching with the blade roller (Vaisman et al., 2011; Halde et al., 2012), using a wide blade cultivator or flail mower (Podolsky, 2013) and mowing using other machines (Blackshaw et al. 2010b). One option that has received less attention is grazing. Grazing is known to improve N availability (Carvalho et al., 2010), reduce weed pressure (Hatfield et al. 2007c; Tracy and Davis, 2009) and prepare an appropriate (i.e., levelled and free of large soil clumps) seedbed for the next crop. Therefore, grazing can serve as a management tool to reduce tillage in organic agriculture.

A series of field experiments were established to investigate the prospect of optimizing N benefits from green manures in organic agriculture. The objectives of these studies were to identify green manure species and green manure management options to maximize N benefit to following cash crops and explore the opportunities to reduce tillage during the green manure phase of the rotation. This involved identifying green manure species and green manure management options to maximize N benefit to subsequent cash crops. Four green manure systems were tested including double-cropped green manures, relay-cropped green manures, full season green manures, and catch crops after grazed full season green manures. Three green manure management options were tested; soil incorporation with tillage, grazing and no-till.

2. LITERATURE REVIEW

2.1 Nitrogen in Organic versus Conventional Agriculture

2.1.1 Nitrogen Macro Level Dynamics

Early successional ecosystems are often N limited (Menge et al., 2012). Agricultural soils under annual crop production are constantly kept at early successional states and, unless nutrients are provided from external sources, they are in short supply. Before industrial synthetic-fertilizer-based agriculture, plant available N was obtained through legume N_2 fixation and from soil organic N reserves. Some legumes are distinguished from other cover crops by their ability to fix atmospheric N_2 through a symbiosis with soil bacteria commonly called "*Rhizobia*". The Leguminosae or Fabaceae family is one of the most important groups of crops for agricultural production as a result of their ability to fix atmospheric nitrogen in agroecosystems. Of the approximately 169 million metric tonnes (Tg) N added to the agroecosystems every year, some 33 Tg are fixed by grain and pasture legumes (Galloway et al., 2004), saving around US$10 billion on fertilizer N each year (Howieson et al., 2008). Alfalfa, for instance, is the fourth most important crop in the USA and worth $7 billion annually (Graham and Vance, 2003). Biological nitrogen fixation is the hallmark of legumes that could be considered the most important biological process on the planet after photosynthesis (Howieson et al., 2008).

Managing N availability is a challenge in conventional and organic systems. In conventional systems, up to 50% of applied synthetic N fertilizer is not utilized by plants and lost to the environment; around 5% is stored as soil N, approximately 25% is emitted to the atmosphere, and around 20% is discharged to aquatic systems (Janzen et al., 2003; Galloway et al., 2004). If managed correctly, legumes offer a better alternative by reducing N losses, thus providing both financial and environmental benefits (Crews and Peoples, 2004). Well-managed organic and legume-based cropping systems are known to retain more soil C and N than conventional systems (Drinkwater et al., 1998; Lynch, 2009). In their meta analysis, Tonitto et al. (2006) found 40% less N leaching loss in legume-based systems as compared to synthetically N fertilized systems.

Legume-based cropping systems have been shown to be more sustainable than conventional and animal manure-based systems (Snapp et al., 2005; Cherr et al., 2006; Tonitto et al., 2006). Some of the benefits of legume-based systems are; i) reduced P loading or soil salinization compared to animal manure application ii) reduced transportation costs, iii) slow release of N, thus, better synchrony with plant uptake and as a result increasing N-uptake efficiency and crop yield N, iv) reduced leaching losses, v) increased soil organic matter and microbial biomass, vi) better nutrient retention and N-uptake efficiency than soils receiving synthetic fertilizers, vii) reduced erosion and nutrient or pesticide losses, viii) suppression of weeds and diseases, ix) suppression of specific crop pests as well as providing habitat or resources for beneficial organisms, and finally, x) release of growth-promoting substances. These benefits have been reviewed in many different articles (Elgersma and Hassink, 1997; Lu et al., 2000; Zentner et al., 2004; Tonitto et al., 2006).

2.1.2 Nitrogen Micro Level Dynamics

Organic agriculture relies more on soil chemical and biological processes for nutrient cycling than conventional agriculture (Stockdale and Watson, 2009). As such, the need for healthy functioning soil is greater under organic management. Healthy soil is defined as the capacity of a living soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health (Doran et al., 2002). Superiority of soil quality and health indicators under organic management has been well documented (Stark et al., 2007; Wu et al., 2008). For instance, organic soils have higher microbial diversity (Yeates et al., 1997; Mader et al., 2002), arbuscular mycorrhizal fungi (Entz et al., 2004), insects and arthropods (Drinkwater et al., 1995) than soils under conventional agriculture.

The differences between organic and conventional soils are not limited to quantitative differences between soil organisms. Increased functional diversity in soils under organic management has also been demonstrated (Mader et al., 2002). The comparison of soils under long-term organic and conventional management showed that organic soils host greater number of genera that are involved in nitrogen fixation, suppression of plant diseases and promoting plant growth (Li et al., 2012).

Organic soils contain more C than conventional soils particularly when manure and compost are used as additional fertility sources (Fließbach et al., 2007). On the other hand, intensive annual organic rotations with no manure or compost additions may deplete subsoil C compared to conventional rotations (Bell et al., 2012). One of the outcomes of higher C input to soils is that soil inorganic N levels are lower in organic systems than in conventional systems (van Diepeningen et al., 2006). When soil inorganic N levels are low, legumes obtain more of their N through N_2 fixation, instead of depleting the soil organic N pools (Bolan et al., 2004; Schipanski et al., 2010). Lower soil inorganic N levels in organic systems also increases the reliance on the mineralization from soil organic N pools. Further, since organic systems contain higher abundance of genes involved in N cycling compared to conventional systems (Xue et al., 2013), improved N availability may be expected under organic management.

Availability of N from soil organic N pools in green manure systems is determined by the efficacy of microbial degradation processes. For instance, soil incorporated green manures release N faster than herbicide-terminated (Mohr et al., 1999) or surface-mulched green manures (Vaisman et al., 2011). Faster N mineralization from soil incorporated green manure biomass has been attributed to greater contact with soil microorganisms. Because of this dependence on microbial degradation, N mineralization and availability patterns under legume-based systems are fundamentally different than synthetic fertilizer-based systems.

2.2 Legume-Based Green Manure Systems in Western Canada

Green manures can be composed of a solo species or an assembly of different species and used mainly as soil amendment and nutrient source for the subsequent crops (Cherr et al., 2006). The common strategy for adding N to organic systems in the northern Great Plains is the use of leguminous green manures (Entz et al., 2001). Green manures can also be used as annual forages (Entz et al., 2002). Although organic farmers use green manures extensively, there is no information as to which species or mixtures are most commonly used in western Canada. For conventional systems, there are a number of reviews reporting on the productivity, forage potential and nutritive value of annual green manures (McCartney et al., 2008; 2009; McCartney and Fraser, 2010).

In legume-based systems N availability is mainly a function of green manure biomass accumulation, which determines the amount of N available, and green manure management, which determines the speed of N release and the fate of released N. Figure 2.1 shows the conceptual representation of components of potential green manure systems to achieve optimum N. A green manure system is composed of time of green manure growth (i.e. full season, late season), management type (i.e. tillage, reduced-till, grazing) and species. Optimum N is achieved through ideal combination of these components. Organic cropping systems must be designed to optimize the synchrony between the N release from green manures and the cash crop N demand (Crews and Peoples, 2005). For instance, among the common green manure systems in the northern Great Plains is full season pea/oat mixture which is incorporated with tillage (Figure 2.1).

Organic systems can be N limited as a result of: i) low legume biomass production, N contribution and subsequent low N availability (Biederbeck et al., 1996), ii) fast N mineralization resulting in losses (i.e. N leaching and volatilization), and resulting poor N availability (Sarrantonio and Scott, 1988), and iii) slow N mineralization from green manure biomass while having large N stocks (Vaisman et al., 2011). The first issue relates to species performance under site-specific conditions and requires selection of species for various environmental niches. The last two issues are implicated in soil and plant N mineralization-immobilization balance and can be influenced by management of green manures (i.e. tillage, mulching, grazing). While the second and third issues are management induced, the first depends on the green manure species selection. Hence, optimum N availability is a result of interaction between ideal green manure species and optimum management (Figure 2.1).

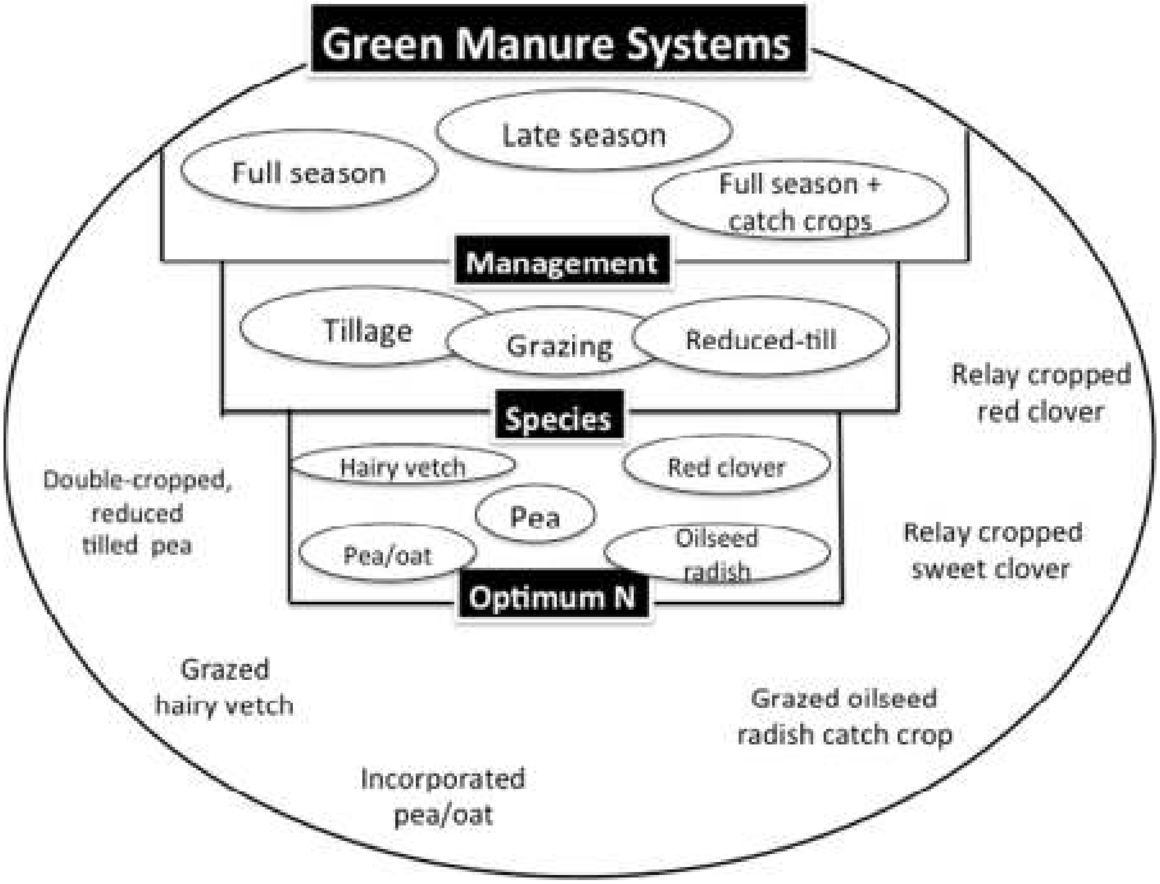

Figure 2.1. Conceptual representation of components of potential green manure systems to achieve optimum nitrogen (N) availability. A green manure system is composed of time of green manure growth (i.e. full season, late season), management type (i.e. tillage, reduced-till, grazing) and species. Optimum N availability is achieved through ideal combination of these components. Some of the potential green manure systems resulting from the interaction of green manure timing, management and species are double-cropped reduced tilled pea, incorporated pea/oat and relay-cropped red clover.

Nitrogen accumulation of green manures is a function of species type (Haynes et al., 1993), biomass production (Peoples et al., 2001), competition within inter-seeded species (Schipanski and Drinkwater, 2011) and the initial fertility of the soil (Peoples et al., 1995). It may be possible to approximate the amount of green manure biomass needed to match productivity of organic systems to conventional systems. Tonitto et al. (2006)

determined that green manures must provide at least 110 kg ha^{-1} of legume-N to make organic (or legume-based) yields to equivalent to conventional yields. Assuming 20% green manure N recovery by the following crop (Ladd et al., 1983; Janzen et al., 1990), 110 kg N ha^{-1} green manure N would translate into 20-25 kg ha^{-1} fertilizer N (at 50% fertilizer-N recovery). Similarly, Wiens et al. (2006) also found that N content of 116 to 208 kg ha^{-1} in alfalfa mulch was required for organic wheat yields to be equivalent to yields in fertilizer based systems with 20 to 60 kg ha^{-1} NH_4NH_3 application. Green manure N content of 110 kg ha^{-1} appears to be a plausible threshold for matching organic yields to conventional ones. Based on the average green manure N concentration of 2.5% (Peoples et al., 2001) green manure dry matter production in organic systems must be around 5000 kg ha^{-1} to produce approximately 125 kg ha^{-1} of green manure N.

In western Canada, a number of green manure species and mixtures have been shown to produce more than 5000 kg ha^{-1} of above ground dry matter biomass. McCartney and Fraser (2010) reviewed the potential annual green manure species for various productivity parameters in Canada. Species that reliably produced more than 5000 kg ha^{-1} when grown for one season were alfalfa, hairy vetch (*Vicia villosa*), berseem clover (*Trifolium alexandrinum*), Persian clover (*Trifolium resupinatum*), yellow sweet clover (*Mellilotus officinalis*), lupin (*Lupinus albus*), forage pea (*Pisum sativum*) and soybean (*Glycine max*). Another extensive review by Cherr et al. (2006) including studies from the USA, Canada and Europe reported crimson clover (*Trifolium incarnatum*), kura clover (*Trifolium ambiguum*) and alsike clover (*Trifolium hybridum),* to produce more than 5000 kg ha^{-1} of biomass. Both reviews showed that when interseeded with other species such as rye (*Secale cerale*), barley (*Hordeum vulgare*) and oat, almost all the legume/grass mixtures had greater dry matter productivity than monocropped legumes. Depending on the species and the location, the biomass increase obtained from interseeding of legumes and grasses ranged from 10 to 90%.

2.2.1 Full season green manures

Green manures can be included in rotations in a number of ways, most commonly as full season crops seeded in spring and incorporated in mid to late summer (Figure 2.1). In Manitoba, Vaisman et al. (2011) seeded a mixture of pea and oat green manure as a full season green manure under organic management at two sites in western Canada. They reported 5800 kg ha^{-1} of biomass production in Manitoba, compared to a Saskatchewan site in which pea alone produced 1800 kg ha^{-1} as a result of dryer conditions and weed pressure. Winter hardy perennials such as sweet clover, red clover, and alfalfa have been used as full season green manures. These crops are usually underseeded to wheat or other cereals and produce substantial amounts of biomass a year after wheat harvest. In Alberta, Blackshaw et al. (2001a) reported average of dry matter yield of 10100 kg ha^{-1} for sweet clover terminated in early July. Ross et al. (2009) also tested four annual clovers (*Trifolium*) species [balansa (*T. michelianum* Savi), berseem, crimson, and Persian, as well as, three perennial clovers; alsike, red and white Dutch (*T. repens*)] were tested as green manures in two locations in Alberta. All clovers were seeded in early July and terminated by mid to late October. Averaged over years (2) and locations (2), annual clovers produced from 3300 to 6800 kg ha^{-1}, while perennials produced 2000 to 3300 kg ha^{-1} of biomass. This indicates that annual species of legumes may be preferred over perennial species for biomass productivity. In the semi-arid Canadian Prairies green manures were generally used as a fallow replacement; seeded in spring and terminated in early summer before green manures reach maturity (Biederbeck et al., 1993). In Saskatchewan, Zentner et al. (2004) reported a 10-year average dry matter production of 2900 kg ha^{-1} for black lentil used as fallow replacement.

Research in the Canadian prairies has investigated the N contribution from annual green manures mainly in annual grain-fallow systems (Zentner et al., 2004). When grown as partial (i.e. terminated at full bloom) fallow replacement in the semi-arid prairie, black lentil, tangier flatpea (*Lathyrus tingitanus*), chickling vetch and field pea biomass contained 40, 33, 49, 62 kg ha^{-1} of N, respectively in Saskatchewan (Biederbeck et al., 1996). In Saskatchewan, greater biomass production by legumes conducted in dry sub-humid environments, resulted in greater N content of legume biomass; 166, 108, 119, 81 and 36 kg ha^{-1} of N for pea, lentil, faba bean (*Vicia faba*), tangier flatpea and seedling alfalfa, respectively (Townley-Smith et al., 1993). When grown as full season green manures, biomass N content of some perennial and annual clovers ranged from 44 to 110 kg ha^{-1} of N (Ross et al., 2009). There appears to be great variability in the ability of different legume species to produce biomass, thus accumulate N.

Intercropping legumes and cereals offer many advantages over legume monocroping (Malezieux et al., 2009). The rationale for intercropping depends on the end goals and the challenges present in a particular farming system. For instance, in organic systems, one of the challenges is competition with weeds. Since legumes are, in general, weaker competitors than other species, cereals can be used as nurse crops to reduce weed competition (Liebman and Dyck, 1993; Hauggaard-Nielsen et al., 2001). Legume cereal mixtures (i.e. pea/oat or pea/barley) and grass-clover mixtures are also commonly used as forage crops in the northern Great Plains (Carr et al., 1998) and in Europe (Krauss et al., 2010; Azo et al., 2012). Green manure mixtures can also be designed to include species with different functional traits to improve not only biomass production, but also N mineralization and biomass decomposition rates. For instance, N mineralization can be balanced through mixing of low (legume) and high (grass) C:N ratio species in a way that supplies N in synchrony with the crop demand (Teasdale and Abdul-Baki, 1998). Adding grasses to legume monocultures may double the C:N ratio of green manures from 10-15:1 to 20-25:1 (Ranells and Wagger, 1997). Grass/legume mixtures such as pea/oat and pea/barley are becoming standard green manures for low-input, organic and reduced tillage systems (personal communication with organic farmers G. DeRuycks of MB and I. Cushon of SK).

2.3.2 Late season green manures

Dedicating the whole season to grow cool or warm season green manures may not be feasible for some producers. There are some green manuring options that can be used within a grain production year. For instance, winter cereal production may allow for establishment of double or relay crops because of earlier grain harvest (Thiessen Martens and Entz, 2001a). Relay cropping is a common practice in regions with a longer growing season and higher precipitation than western Canada (Blaser et al., 2007; Queen et al., 2009). Relay cropping involves seeding or broadcasting a small seeded leguminous crop early in the spring into a winter cereal stand. Legumes establish under the canopy of winter cereals and continue producing biomass after the winter grain harvest. Relay cropping, especially using red clover and alfalfa, has received more attention than double cropping in temperate regions (Thiessen Martens et al., 2001b; Blackshaw et al., 2010a). Double cropping involves seeding a green manure after the main crop harvest. Double cropping is rarely investigated in the northern Great Plains, perhaps as a result of the short growing season making biomass production after main crop harvest challenging. In Manitoba, under conventional management, Thiessen Martens et al. (2001b) reported 746 and 634 kg ha^{-1} of biomass production for double-cropped chickling vetch and lentil, respectively.

There is very limited information on late season green manure N accumulation. In Iowa under conventional management, N content of relay cropped red clover and alfalfa biomass were 158 and 69 kg ha^{-1} respectively (Liebman et al., 2012). In Ontario relay cropped red clover biomass contained 44 to 98 kg ha^{-1} of N under conventional management (Vyn et al., 2000). In the Canadian Prairies, there are no reports of late season green manure N accumulation but fertilizer N replacement values of relay cropped alfalfa, red clover as well as double-cropped chickling vetch and lentil were reported to be 36, 25, 36, and 31 kg N ha^{-1} respectively for an oat crop grown in Manitoba (Thiessen Martens et al., 2005)

2.2.3 Catch Crops – a New Concept for Western Canada

Catch crops are plants grown in specific niches in order to capture excess soil nutrients. In conventional systems catch crops are commonly seeded after main crop harvest to capture and sequester excess N (Herrera et al., 2010). In organic systems, catch crops are generally seeded after animal manure application to capture excess nutrients (Olesen et al., 2000) but rarely seeded after green manures. Catch crops are commonly used in regions with high precipitation such as northern Europe and New Zealand to prevent NO_3-N leaching (Di and Cameron, 2002; Thorup-Kristensen et al., 2003). In dry areas, such as in western Canada, catch crops are not commonly used. Though small, leaching of NO_3-N is documented in western Canada when precipitation is higher than average (Campbell et al., 2006).

Nitrate is of particular importance in catch crop research. As a result of its negative charge, NO_3-N is highly mobile and can leach when N supply exceeds crop requirements. Nitrate leaching in agroecosystems is influenced by soil type, catch crop species, precipitation, temperature, N transformation rates (mineralization, immobilization, dentrification), N input type, drainage and tillage (Campbell et al., 2006; Constantin et al., 2010). Among these factors, catch crop species selection, management and N input type are among the most effective management tools for controlling NO_3-N leaching (Thorup-Kristensen et al., 2003; Constantin et al., 2010). Catch crops were found to decrease N leaching by 40-50% in conventional (Aronsson and Torstensson, 1998) and 30-38% in organic systems (Askegaard et al., 2005).

Excess precipitation is one of the main reasons for NO_3-N leaching (Thorup-Kristensen et al., 2003). Therefore, catch crop research has been concentrated in areas where annual precipitation is generally above the crop demand (i.e. north eastern USA, New Zealand and Northern Europe). Under such conditions, catch crops can limit NO_3-N loss by direct uptake of available NO_3-N and/or utilization of excess moisture, hence preventing downward water-bound NO_3-N movement (Thorup-Kristensen et al., 2003). Even under the relatively dry conditions in western Canada, Campbell et al. (1984) showed that NO_3-N leaching occurs when precipitation was above the long-term average. Nitrate leaching was more severe in rotations with fallow periods than intensive rotations with crops grown every year.

Recently most of the attention on catch crop research has been on species selection and tillage management for maximum NO_3-N uptake and synchronized N release from catch crops to cash crops (Constantin et al., 2010; Askegaard et al., 2011). Species selection in catch crop studies is an important factor because N uptake capacity of catch crops is determined by speed of establishment, growth rate, rooting depth and cold tolerance (Munkholm and Hansen, 2012). The species selection not only affects N uptake, but also N availability to the subsequent cash crop from decomposing catch crop residue. The roots of catch crops can reach the depth of 150 cm depending on the species (Thorup-Kristensen et al., 2001).

In European organic crop production, catch crops are used because; i) excess manure application during grain production leaves some N susceptible to leaching after grain harvest, and ii) as part of the organic regulations special attention is paid to keep ground covered and build soil organic matter with the use of catch crop biomass. Catch crops can also be treated as winter cover crops (Sainju et al., 1998). Standard green manure management practice in the northern Great Plains involves incorporation of green manures into soil, which leaves soil exposed. Catch crop biomass would provide additional C and soil cover.

Catch crops can play a special role when grazing is combined with green manuring in organic systems. For example, because of greater availability of nutrients in grazed green manures systems (Carvalho et al., 2010), catch crops may be used to capture excess nutrients after grazing of green manures. This new approach would intensify the green manure phase of organic rotations by adding grazing animals and catch crops. Grazing animals utilize green manures which otherwise is a lost revenue opportunity for the farmer. Catch crops seeded after grazing can increase the biomass production on the same land base within one growing season. Long-term experiments with catch crops have shown that adding organic matter and fertility through the use of these crops increases productivity of the land (Constantin et al., 2010; Doltra and Olesen, 2013).

Catch crop species selection not only affects N uptake potential, but also N availability to the subsequent cash crop from decomposition of catch crop residue. Therefore, C:N ratio, lignin and N content of the catch crop species are important characteristics to be considered when selecting a catch crop species or mixtures (Thorup-Kristensen et al., 2003). One of the main challenges in legume-based systems is achieving the synchrony of N mineralization from green manures and cash crop N demand (Crews and People, 2005; Tonitto et al., 2006). In general N mineralization in crops with low C:N ratio (i.e. some brassicas and legumes) is faster than crops with high C:N ratio (i.e. grasses). Accordingly, ideal catch crop species should be able to capture readily available N after grazing and release it in synchrony to meet the N needs of the next crop. Grasses such as Barley (*Hordeum vulgare*) may be effective in capturing N because of its fast growth but releases N more slowly because of its high C:N ratio. Alternatively, brassicas such as oilseed radish (*Raphanus sativus*) could be faster in releasing N to the cash crops as a result of its lower C:N ratio than grasses.

All of the late season green manure options have potential to increase functional and phenological diversity of plants. Further, late season green manure biomass can also be considered as forages or late season green manures for soil amendment. Considering that increased phenological diversity increases productivity (Stevens and Carson, 2001), increasing the presence of green manures and livestock should improve system performance.

2.2.4. Annual Forages as Green Manures

Annual forages maybe used as green manures and supplement feed shortages in livestock production (Shrestha et al., 1998). Although forage potential of many annual forage species has been evaluated, very few studies have used actual grazing as a management effect (McCartney et al., 2008). Most research has focussed on hay or silage potential of annual forages (McCartney et al., 2004). Some annual green manures have been used as dual-purpose crops, where the first growth is harvested as forage and the second growth is soil incorporated as green manure to provide N to the subsequent crop. When used as dual-purpose crops (i.e. berseem clover and alfalfa), N benefit from forages are similar to green manures (Shrestha et al., 1999). Grazing forages, instead of removing them as forages, may provide an additional N benefit to the following crops. In Georgia, total soil N levels were 34% higher under long-term grazed pastures than hayed pastures (Franzluebbers et al., 2000).

In integrated crop-livestock systems, annual forages are expected to serve as both animal feed and soil fertility amendments. There is a need to establish the effect of grazing of annual forages on soil fertility and subsequent crop productivity. In conventional systems, nutritional composition and dry matter productivity of number of annual forages have been investigated (Fraser et al., 2004; May et al., 2007). However, there is little information on weed competitiveness and palatability of potential green manure species. In organic systems, where soil management history may produce different soil fertility (van Diepeningen et al., 2006) and weed pressure (Ryan et al., 2010) than conventional systems, such information is critical. Therefore, selection criteria for annual forages in organic systems should include: i) sufficient dry matter biomass production for livestock, ii) nutritional quality and palatability, iii) nitrogen contribution to following cash crops, and, iv) weed competitiveness.

2.3 Nitrogen Mineralization from Green Manures

The main source of N in legume-based systems is the decomposing organic matter from legume green manure plant biomass, including nodules. Legume nodules contain several times more N than legume shoots and roots. Nitrogen concentration of legume shoots could be 30% greater than legume roots (Biederbeck et al., 1996). The proportion of N that is mineralized from decomposing green manures and availablity to cash crop ranges from 10-30% of the total applied N (Ladd et al., 1983; Janzen et al., 1990). The proportion of green manure applied N that is retained in the soil during the first cash crop year ranges from 40 to 80% (Ladd et al., 1983; Janzen et al., 1990). In comparison to fertilizer-based systems, leaching and gaseous losses from legume-based systems are lower but can change with management (Campbell et al., 1994). While only 0.1 to 0.5 % of the green manure applied N is lost through volatilization when incorporated, volatilization losses can be up to 7% of total green manure applied N when left on the soil surface (Janzen and McGinn, 1991; Vaisman et al., 2011).

In legume-based organic crop production, N is acquired from N_2 fixation through a legume-*Rhizobium* symbiosis. Once N is captured in legume biomass it needs to be transformed into plant available inorganic N (i.e. NH^+_4 and NO^-_3). Transformation of organic N to inorganic N is a microbialy mediated process. There are two "microbial mediums" that can facilitate the conversion of organic N into inorganic N; the soil and the rumen of animals. Bacteria in the rumen can degrade the cellulose cell walls of plant cells and make N-rich compounds such as amino acids and proteins available for digestion (Reynolds and Kristensen, 2008). Ruminants only retain 10-35% of the N from digestion of feed and the rest is deposited as dung or urine (Williams and Haynes, 2000). Hence, there is a great potential to utilize this excreted N in crop production.

2.3.1 Plant Decomposition in Soil versus Rumen

Green manures are often incorporated into soil to improve soil microbial contact to plant material, which accelerates the N mineralization from plant material. However, microbes in the rumen of animals are more efficient in transforming organic N to inorganic N than microbes in soil (Chesson, 1997). Chesson (1997) suggested six important benefits of the rumen compared with soil for degradation of plant material:

i) the controlled and near constant environmental conditions maintained in rumen;
ii) the general absence of limiting factors such as the supply of N and P in the rumen environment;
iii) the highly anaerobic nature of the rumen environment and the absence of degradation processes dependent on molecular oxygen;
iv) the high numbers of viable microorganisms adapted to rumen conditions and their inability to survive elsewhere;
v) the aqueous nature of the rumen environment;

vi) the animals' preference for the consumption of green plant material with readily degradable cell walls and, given the opportunity, the ability of the grazing animal to select the most degradable material.

Improved nutrient cycling and N mineralization upon grazing have been shown in various ecosystems (Hobbs, 1996; Tracy and Frank, 1998). Urine is mostly (60-90% of urinary N) urea, while faeces is mostly composed of less plant available organic N (Whitehead, 2000). Since most of the N in urine is in urea form, upon reaching the soil, urea N hydrolyses to plant available NH^{+}_{4}, which can be oxidized to other plant available mineral N forms; NO^{-}_{2} and NO^{-}_{3}. Nitrogen content of faeces is less affected by forage quality than is urine N. For instance, when ruminants graze green manure with N concentration of 4%, up to 80% of the N is deposited in the urine (Haynes and Williams, 1993).As the quality of forage increases (i.e. low C:N ratio), urine N content increases (Haynes and William, 1993). Green manures are generally grazed before reaching maturity, hence the portion of the plant material entering the rumen is expected to have low C:N values.

Nitrogen mineralization in grazed systems is strongly affected by forage quality and quantity, as well as soil physical conditions (Schrama et al., 2013). Nitrogen mineralization from faeces increases with the increasing N concentration and decreasing C:N ratio of the faeces, which are related to digestibility and N concentration of the feed (Kyvsgaard et al., 2000). Hence, ruminants consuming high quality feeds such as legumes are expected to excrete high amounts of N in faeces and urine, unless legumes contain tannins and phenolic compounds, which reduce feed digestibility (Rufino et al., 2006). The high N content of urine can be beneficial in crop production, however, an animal diets rich in N may increase the risk of N losses through leaching (Ryden et al., 1984) and gaseous emissions (Oenema et al., 1997).

The size of a ruminant animal species can have a direct impact on N cycling (Bakker et al., 2004). For instance N loading under urine patches for sheep is usually half that of cattle, which reduces the risk of N losses (Di and Cameron, 2002). Also, sheep urinate more often (18-20 times day^{-1}) than cattle (10-12 times day^{-1}), thus distribute urine N more evenly across the fields (Williams and Haynes, 1995).

2.3.2. Tillage in Organic Green Manure Systems

Organic agriculture is criticized for its reliance on tillage to control weeds and mineralize N (Trewavas, 2004). In conventional systems, on the other hand, land area under no-till have been rapidly expanding; 35% and 56% of all cropped land in the USA and Canada respectively, are now under no-till methods (Horowitz et al., 2010; Statistics Canada 2013). Attempts to reduce tillage in organic systems have often focused on reducing, rather than completely eliminating tillage (Berner et al., 2008; Krauss et al., 2010). When tillage was completely eliminated, crop productivity in no-till organic systems was significantly reduced as a result of N immobilization and increased weed competition (Legere et al., 2013; Delate al., 2011). In reduced tillage organic systems, however, soil quality parameters and crop productivity appear to be similar to conventional no-till (Berner et al., 2008; Krauss et al., 2010; Cavigelli et al., 2013).

Reduced productivity in no-till organic systems is generally attributed to slower N mineralization from organic matter (Sarrantonio and Scott, 1988) especially when the cash crop is a cereal. Slow N mineralization under no-till is a result of low soil temperatures and limited contact of plant material to soil (Franzluebbers et al., 1995). Placement of plant material on soil surface limits the soil microbial population access to this substrate and slows N mineralization (Varco et al., 1993). Limited soil N availability under no-till have shown to increase lentil and field pea N_2 fixation by 10 and 31%, respectively compared to when these legumes were grown under conventional tillage (Matus et al., 1997).

The green manure phase of an organic rotation is generally the most suitable for implementing reduced tillage to control weeds (Peigne et al., 2007). Consequently, most research on reduced tillage has focussed on green manure termination method and timing to suppress weeds (Carr et al., 2011; Shirtliffe and Johnson, 2012). However, in reduced tillage organic systems, green manures are expected to provide several services, most important of which are weed suppression and N supply. There may be compromises in attempting to achieve either one of these two objectives. For instance, the need for a thick green manure mulch to suppress summer annual weeds requires long lasting (i.e. slow decomposition) green manures with high C:N ratio. Teasdale and Mohler (2000) showed that approximately 8000 kg ha^{-1} of mulch was required to inhibit the emergence of weeds. However, such green manures may not supply enough N for the cash crop as a result of slow N mineralization (Leavitt et al., 2011). Monoculture legume mulches, on the other hand, decompose fast (Wagger et al., 1998), hence may not provide effective weed suppression.

Legume/grass mixtures offer a viable alternatives to monocultures comprised of either legumes and cereals. Carbon:N ratio in such mixtures may be manipulated to match the specific needs of the system. Legume/grass mixtures have been shown to decompose and release N faster than monoculture grasses (Rosecrance et al., 2000). However, achieving synchrony between N mineralization from mulches and cash crop N uptake have proven difficult when tillage was eliminated from the system (Vaisman et al., 2011; Carr et al., 2011).

Very few studies have investigated the N dynamics under reduced tillage organic systems. Most of the focus of previous no-till organic research has been on weed suppression. One reason is the geographical location of organic reduced tillage research; research has been conducted in areas where animal manures were readily available, which provide readily available N to the system. For instance, in northern Europe researchers use manure compost to supplement nutrients in organic systems (Krauss et al. 2010). Similarly in mid-Atlantic USA, researchers use chicken or cattle manure (Teasdale et al., 2007). As such, researchers in these regions have explored options of side-dressing animal manure, in conjunction with various proportions of grass/legume mixtures, to improve N synchrony (Delate et al., 2008; Mirsky et al., 2012).

In the northern Great Plains, animal manures may not be as easily available as a result of lower farm numbers and greater distances between crop and livestock operations. Annual and perennial green manures are the primary source of nutrients in organic systems of western Canada (Entz et al., 2001). Although annual green manures may provide N benefits to the subsequent crops, the effect is often short lived, diminishing after the first cash crop harvest (Bullied et al., 2002). Soil mineral N content in organic reduced tillage systems with no external inputs is also generally lower than conventional systems (Miller et al., 2008). In Manitoba, soil NO_3-N content in rolled (i.e. mulched) pea/oat plots was half of that of tilled pea/oat plots in the autumn of the green manure year (Vaisman et al., 2011). Nevertheless, these same authors found that soil NO_3-N was conserved under reduced tillage treatment compared to the tilled treatment. After two years, the authors found that soil in reduced tillage treatments contained 31 kg ha^{-1} more NO_3-N than in soils that were tilled. Faster recycling and strategic transfer of nutrients may be achieved if grazing animals are integrated into organic reduced tillage systems (Miller et al., 2008; Thiessen Martens and Entz, 2011).

2.4. Post Green Manure N Availability

Although the N content of green manure biomass is not always an accurate predictor of N mineralization or N benefit to the subsequent crop (Liebman et al., 2012), it illustrates the potential of green manures to improve the N supplying capacity of legume-based systems. Determining net N mineralization from plant biomass under field conditions is challenging because of the volatile and mobile nature of various N compounds and most agronomic studies are not equipped to measure all aspects of the N cycle. There are three methods commonly used in agronomic studies to measure green manure N supply to following crops: i) fertilizer replacement value of green manures (FRV; Hesterman et al., 1992), ii) cash crop uptake of labeled ^{15}N green manure, and iii) direct comparison of test crop productivity grown in green manure amended plots compared with test crops grown in non-amended plots.

In Manitoba, Thiessen Martens et al. (2005) established FRV for an oats from relay cropped alfalfa (36 kg N ha^{-1}) and red clover (*Trifolium pretense)* (25 kg N ha^{-1}), as well as for double-cropped chickling vetch (36 kg N ha^{-1}) and lentil (31 kg N ha^{-1}). In Iowa, greater FRV for corn were reported by Liebman et al. (2012) for relay cropped alfalfa (95 kg N ha^{-1}), and red clover (135 kg N ha^{-1}). Observed differences may be attributed to longer growing season and greater biomass production in Iowa as compared to the Manitoba study. Nevertheless, FRV may not be a true representation of N benefit from green manures as non-nutritional benefits from green manures have also been shown to improve test crop productivity (Janzen and Schaalje, 1992; Garand et al., 2001). Labeled ^{15}N green manure can also be used to determine the fate of green manure N, however, the pool substitution effect (i.e. labeled ^{15}N substitutes indigenous soil N) may cause underestimation of N benefit of green manures (Janzen et al., 1990).

In organic agriculture synthetic N fertilizers are not permitted, hence, FRV may not be an appropriate gauge for organic systems to assess N benefit from green manures. Also, green manures in organic systems are expected to provide multiple benefits besides the N contribution (non-nutritional benefits such as weed and disease control, soil organic matter building, growth promoting substances). In a labeled ^{15}N study, Janzen and Schaalje (1992) showed that, for a given amount of fertilizer and green manure N, barley grown in green manure amended pots had increased yields compared to barley grown in pots receiving N fertilizer. The authors attributed the higher yields in green manure system to the non-nutritional benefits. Therefore, direct comparison of test crop productivity grown in green manure amended plots and test crop grown in non-amended plots may be more appropriate for organic systems.

Under conventional management with no N fertilizer, Bullied et al. (2002) found that compared to wheat grown after a fertilized (70 kg ha^{-1} of N fertlizer) canola (*Brassica napus*) crop, wheat grown after chickling vetch and lentil contained 73 kg ha^{-1} and 53 kg ha^{-1} more N, respectively. Wheat (*Triticum aestivum*) grown in alfalfa berseem clover (*Trifolium alexandrinum*) and red clover plots contained 39, 27, and 43 kg ha^{-1} more N than wheat grown in canola plots. Similarly, in Alberta, N uptake of barley was approximately 50% greater when grown after clovers (berseem, crimson, Persian, alsike, red and white Dutch) than grown after rye (*Secale cereale*) (Ross et al., 2009).

A series of field experiments were established to investigate the prospect of optimizing N benefit from green manures in organic agriculture. The objectives of this study were to design and test green manure systems compatible with intensive annual crop production. This involved identifying green manure species and green manure management options to maximize N benefit to subsequent cash crops. We hypothesized that;

i) Green manures can be included in organic crop rotations as double and relay crops without compromising annual cash crop production and provide N benefit.

ii) Productivity and N benefit of no-till seeded double crops would be similar to conventional seeded double crops.

iii) Grazing green manures will increase the N availability in comparison to the common practice of soil incorporation with tillage.

iv) As a result of increased N availability after grazing, no-till seeded catch crops will perform similar to conventional seeded catch crops.

v) Catch crops will reduce the leaching of NO_3-N after grazing of green manures compared to no catch crop treatments.

vi) Wheat yields following catch crops will be greater than yields with no catch crop.

These hypotheses address crucial issues regarding the improvement of N availability and reduced soil disturbance in organic cropping systems of temperate regions. None of the proposed systems has been investigated under organic management in temperate regions. The first hypothesis explores the possibility of inclusion of green manures in organic rotations without sacrificing a cash crop year. The second hypothesis suggests that through inclusion of double and relay crops tillage intensity may be reduced, which is a difficult task to achieve in organic agriculture. The third hypothesis will explore whether is it possible to accelerate and increase N availability from green manures to cash crops when grazing is used as a management tool. The fourth hypothesis will investigate the implications of the third hypothesis in terms of tillage; where greater nutrient availability after grazing may facilitate organic no-till cropping, which is a challenge that has not been resolved. Through the last two hypotheses this study will assess whether highly available N after grazing can be captured and released to cash crops more effectively with catch crops.

CHAPTER 3

PRODUCTIVITY AND NITROGEN BENEFITS OF LATE-SEASON LEGUME COVER CROPS IN ORGANIC WHEAT PRODUCTION

3.1 Abstract

When full-season cover crops are used in organic rotations without livestock, cash crop production is compromised. Including winter cereals in rotations can widen the growing season window and create a niche for late-season cover crops. We investigated the establishment and biomass production of relay-cropped red clover (*Trifolium pratense* L.) and sweet clover (*Melilotus officinalis* L. 'Norgold') and double-cropped cowpea (*Vigna unguiculata* L. 'Iron and Clay'), hairy vetch (*Vicia villosa* L.), lentil (*Lens culinaris* L. 'Indianhead'), soybean (*Glycine max* L. 'Prudence'), pea (*Pisum sativum* L. '40-10'), and oil seed radish (*Raphanus sativus* L*)* as well as wheat response to these crops under reduced tillage (RT) and conventional tillage (CT) at three locations in Manitoba, Canada. Red clover, sweet clover and pea produced from 737 to 4075 and 93 to 1453 and 160 to 2357 kg ha^{-1}of biomass, respectively. All double crops, with the exception of soybean at two site years, established successfully under both RT and CT. The presence of cover crops increased wheat N uptake at stem elongation, maturity and yield, even when the biomass production of cover crops was modest. We conclude that late-season cover crops enhance the following wheat yield and facilitate reduced tillage in organic crop production.

3.2 Introduction

A cover crop may be defined as any crop grown to provide soil cover regardless of whether it is later soil incorporated. Organic farms in the Northern Great Plains (NGP) of

North America typically include legume cover crops in rotation to maintain soil fertility (Entz et al., 2001). However, growing a cover crop for the full season results in loss of that year's cash crop. Cover cropping systems that are in synchrony with the intensive annual organic crop production are required for organic farmers. Relay and double crop systems exploit the heat and precipitation resources available after the main crop harvest. Therefore, organic farmers using relay and double-cropping techniques may be able to harvest a cash crop and benefit from a cover crop within the same growing season.

Late-season legume cover crops are defined as cover crops that are grown alongside or after the cash crop within the same growing season. The terms "double crop" and relay crop" are both considered as late-season legume cover crops. Double-cropping involves seeding a cover crop after the main crop harvest, whereas relay-cropping entails seeding cover crops into an established crop. Although in some regions relay and double cover crop products can be harvested (i.e. double-cropped soybeans after winter wheat in Kansas and Missouri), in the NGP they are commonly grown to provide soil cover, fix atmospheric nitrogen and improve the overall soil health. In this paper we consider relay and double crops as soil fertility-building crops.

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

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

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

Organic land management relies heavily on tillage to control weeds and to mineralize N from green manures. There has been considerable work on reducing tillage in organic systems. Such attempts focus mainly on manipulations during the green manure or cover crop phase of the rotations (Peigné et al. 2007; Vaisman et al. 2011). As a result of better water retention in RT than in CT systems (Krauss et al. 2010), late-season cover crops may establish and produce more biomass under RT than under CT. While N mineralization in long-term, no-till soils is faster than in conventional-tilled soils (Soon et al. 2001), short-term N mineralization is slower in RT systems than in CT systems (Vaisman et al. 2011).

It may be possible to reduce tillage in short-term rotations without an N penalty. However, this requires a plant biomass with low C:N ratio, because net mineralization from indigenous soil N sources increases when the crop residue C:N ratio is low (i.e. C:N

< 20:1; Bremer and van Kessel 1992). Therefore, a question of interest is whether low C:N biomass from late-season cover crops may be able to provide sufficient N to offset the slower mineralization from RT. No NGP studies have investigated reduced tillage in organic late-season cover crop systems.

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

3.3 Materials and Methods

Site Description

This experiment was conducted at three locations in Manitoba, with different soil and climatic conditions: University of Manitoba Ian Morrison Research Farm in Carman

(49°29’ N, 98°0’ W), University of Manitoba Glenlea Research Station (49°64’ N, 97°14’ W), and, DeRuyck’s Certified Organic Farm in Notre Dame de Lourdes (49°54’N, 98°76’ W). The experimental sites at Glenlea and Carman were not certified organic but have been managed based on organic agriculture principles since 1992 and 2003, respectively. No inputs were applied to any of the treatments.

Soils at Carman are well drained Orthic Black Chernozems with a fine sandy loam texture (Mills and Haluschak, 1993). Two meters deep clay substrate underlies the soils, which are lacustrine and deltaic sediments with slope of less than 1%, pH of 6.2, and an organic matter content of 25 g kg^{-1}. Soils in Glenlea are poorly drained Gleyed Humic Vertisols with well-developed Ah horizon overlying a gleyed C horizon (Michalyna et al., 1975). The soils were formed under glaciolacustrine clay floodplain with pH of 7.4, and an organic matter content of 77 g kg^{-1}. The particle size distribution was 60% clay, 35% silt, and 5% sand. At Notre Dame de Lourdes (Notre DL) the soil was Orthic Dark Gray Chernozem sandy clay loam, having a pH of 7.4 and an organic matter content of 57 g kg^{-1}. Soils at this site were formed under glacial lacustrine sediments.

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

The experiment was designed to evaluate cover crops following fall rye with wheat used as the test crop in the subsequent year to determine N availability and yield response. Eight cover crops were tested under two tillage regimes. The experimental design was a randomized complete block with four replicates in a split plot arrangement. The main plots were tillage regime and the subplots were cover crop type. Control plots contained no cover crops. The experiment was replicated at three sites and over two planting years. The experiment started in the autumn of 2007 at Carman and Glenlea locations with the seeding of fall rye (*Secale cereale* L. 'Remington'). In 2009, as a result of floods in Glenlea, the experiment was conducted at Carman and Notre DL. Wheat was used as a test crop for the experiments in 2008 and 2009. For the experiments that started in 2010 and 2011, only the establishment and biomass production of cover crops were investigated. Each experiment started with fall rye cash crop and late-season cover crops in year one. Fall rye was seeded using a JT-A10 air-drill seeder (R-Tech Industries Ltd. Homewood, MB) with a row spacing of 20 cm and a seeding rate of 100 kg ha^{-1}. The fall rye grain was harvested few days before the seeding of double crops as indicated in Table 3.1 from the whole plot using a Wintersteiger (Wintersteiger Inc. Saskatoon, SK) plot harvester.

The relay crops were red clover (*Trifolium pratense* L.) and sweet clover (*Melilotus officinalis* L. 'Norgold'), while, double crops were cowpea (*Vigna unguiculata* L. 'Iron and Clay'), hairy vetch (*Vicia villosa* L.), lentil (*Lens culinaris* L. 'Indianhead'), soybean (*Glycine max* L. 'Prudence'), pea (*Pisum sativum* L. '40-10'), and oil seed radish

(*Raphanus sativus* L.*)*. The seeding rates and the dates (seeding and termination) of double and relay crops are presented in Table 3.1. Hairy vetch was not used in the Notre DL site due to the farmer's concern over hairy vetch's potential to become a volunteer crop (weed) in the following years. In 2010 pea, lentil and hairy vetch were seeded, and in 2011, only red clover, sweet clover, and pea were seeded based on their successful establishment in the previous years.

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

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

Tillage regimes were RT and CT and differed in terms of tillage before seeding and the timing of cover crop incorporation (autumn vs. spring incorporation). In the RT double crop system, double crops were seeded into rye residue with no preseeding tillage, and the land was not tilled until spring-time the following year. In the CT double crop system, rye residue was tilled before seeding the double crops. Further, these plots were tilled in the autumn after double crop growth and in the spring before wheat crop. Since relay crops were hand broadcasted there were no differences in seeding method for relay crops. Thus, RT relay crops were spring incorporated (immediately before wheat seeding) and CT relay crops were tilled in late fall of the rye year and again immediately before wheat seeding. Therefore, RT plots were tilled only once (immediately before spring wheat seeding) and CT plots were tilled 3 times for double crops and 2 times for relay crops before wheat seeding.

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

Data collection

Fall rye biomass (grain + straw) samples were taken at maturity using 1m^2 quadrat randomly placed in each of the four replicates. The cutting height was 3-5 cm from the ground. The samples were dried for two days at 60 ^{o}C and weighed for dry matter content. The reported biomass numbers are the average weight of four replicates.

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

A wheat test crop in year two was only seeded for the 2008 and 2009 experiments. Wheat biomass samples at Carman were taken at stem elongation and maturity from 2 x 0.4 m^2 areas in each plot. At Glenlea, wheat biomass samples were collected at stem elongation and soft dough stages because of the concern regarding wildlife destroying the plots before reaching maturity. Wheat grain for yield estimation was collected from the whole plot using a Wintersteiger (Wintersteiger Inc. Saskatoon, SK) plot harvester. All samples were dried for 2 days at 60 ^{o}C and weighed for dry matter content.

Dry wheat (grain and straw) and cover crop biomass samples were ground with a Wiley Mill (No.1 Arthur H. Thomas Co., Philadelphia, PA). Wheat grain was ground with a Cyclone Lab Sample Mill (UDY Corporation, Fort Collins, CO). All ground samples were subsampled and analyzed for N concentration by combustion analysis using a LECO FP-528 (LECO, St. Joseph, MI). Wheat N uptake at stem elongation, soft dough

(Glenlea) and maturity (Carman and Notre DL) were calculated as the product of biomass production (kg ha^{-1}) and the % N content of the ground wheat biomass sample. Wheat grain % N content was multiplied by 5.7 for the estimation of wheat grain protein (Jones 1941).

All weather related data were obtained from the Environment Canada database (Environment Canada 2013). Growing degree days (GDD) was calculated using 3 ^{o}C as a base temperature with the formula:

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

Statistical analysis

Statistical Analysis Software program (SAS Institute, 2001) PROC Mixed procedure was used for data analysis. We used ANOVA and considered treatment effects as fixed effects and replicates as random effects for all measurements. Relay crop biomass production was analyzed separately from double crops because of differences in management (i.e., seeding date, tillage) between the two systems. Assumptions of ANOVA were tested by using the PROC Univariate procedure. Differences were considered significant at $p < 0.05$ and means were separated using a Fisher protected LSD test. Planned comparisons were analyzed using the “Estimate” statement in SAS. A linear regression model was fitted to explore the relationship between double and relay crop biomass production and wheat N uptake at stem elongation and maturity.

3.4 Results and Discussion

Climate and Field Conditions

Growing season air temperatures, precipitation and GDD in all study years and sites deviated widely from long-term averages (Tables 3.2 and 3.3). Lower than average temperatures and GDD were recorded in 2009 at Carman and Notre DL. In 2010 precipitation was almost double the 30-year average. In 2010 and 2011 growing season air temperatures were much higher than the 30-year average.

As a result of GDD accumulation, fall rye in 2010 and 2011 was harvested much earlier than other years and double crops were seeded by August 8th in Carman (Table 3.1 and 3.2). In a previous Manitoba study, as a result of warmer growing season temperatures, Thiessen Martens et al. (2001) seeded double crops after fall rye on July 29th in 1998 and August 10th in 1999. Fall rye above-ground dry matter values were 13,788 kg ha^{-1} at Glenlea, 15,040 kg ha^{-1} at Carman in 2008, 13,474 kg ha^{-1} at Carman in 2009, 10,901 kg ha^{-1} at Notre DL in 2009, 11,657 kg ha^{-1} at Carman in 2011 and 15,945 kg ha^{-1}at Notre DL in 2011. Biomass production of fall rye in this study is comparable to an earlier Manitoba study where fall rye biomass ranged from 7,611 to 15,375 kg ha^{-1} (Thiessen Martens et al. 2001).

Relay Crop Plant Density and Dry Matter Production

Successful relay crop establishment was observed at five of six site years for red clover and 3 of 6 site years for sweet clover (Table 3.4). Both crops failed to establish at Carman in 2008 presumably due to low precipitation from April to June (Table 3.3). Sweet clover also failed to establish at Notre DL in 2011, perhaps due to a very dense fall rye canopy

(15,945 kg ha^{-1}) competing for light and moisture. Queen et al. (2009) observed reduction in the relay-cropped red clover establishment with decreasing light penetration in wheat. Negative effects of limited soil moisture on relay-cropped red clover establishment was previously reported by Singer et al. (2006) but there are no previous reports for sweet clover when grown as a relay crop.

At some locations, red clover plant density increased from early June to July, perhaps as a result of the hard seed coat of red clover delaying early germination and the favorable growing conditions later in the spring facilitating germination. Queen et al. (2009) noted that relay-cropped red clover plant density progressively increased until 4-6 weeks after planting. They also reported that when precipitation was higher than long-term normals, red clover plant density was more stable during all developmental stages of wheat. In the present study, red clover had significantly higher plant densities than sweet clover at two of five site years. Despite the high seeding rates used in this study (400 seeds/m^2) fewer than 25 % of the seeds developed into seedlings. Blackshaw et al. (2010a) used 200 seeds m^{-2} for red clover and the plant densities in that study were similar to ours. Blaser et al. (2011) and Singer et al. (2006) found that red clover biomass production is independent of plant population densities when there were more than 30 plants m^{-2}.

In all site years, except at Carman in 2009, red clover produced significantly more biomass than sweet clover (Table 3.6). Red clover dry matter biomass production ranged from 737 to 4075 kg ha^{-1} and was greater than previous observations in Manitoba (605 to 1804 kg ha^{-1} Thiessen Martens et al. 2001), or Alberta (10 to 1420 kg ha^{-1} ; Blackshaw et al. 2010a) studies. However, our findings are in agreement with other works from wetter regions such as Ontario (Vyn et al. 2000) and Michigan (Hesterman et al. 1992) reporting

1930 to 4020 kg ha^{-1} and 2250 to 5500 kg ha^{-1} biomass production, respectively. Although there seems to be a trend based on the regional precipitation gradient (i.e. more precipitation, more biomass), biomass production of clovers in our experiment did not respond to fluctuating growing season precipitation (Tables 3.3 and 3.6). Rather, there was an evidence of "carry-over" soil moisture from previous year to increase biomass production. In 2011, growing season precipitation at Carman was 90 mm lower than the 30-year average, but red clover produced 4075 kg ha^{-1} of biomass perhaps as a result of high precipitation in 2010 recharging soil moisture beyond crop requirements in 2011. In 2009, Carman growing season precipitation was equivalent to the 30-year average (386 mm) but red clover produced only 850 kg ha^{-1} biomass. Similarly in 2008, growing season precipitation at Glenlea (397 mm) was close to 30-year average (416 mm) and red clover produced 3696 kg ha^{-1} of biomass. Besides water availability, main crop competition and late-season heat availability are also potential influencing factors for red clover biomass production. Queen et al. (2009) argued that, besides the availability of inexpensive fertilizers, this apparent unpredictability in relay crop biomass production has prevented the wider adoption of relay-cropping.

Double Crop Plant Densities and Dry Matter Production

Double crops were seeded immediately following fall rye harvest after tillage (CT) or in untilled soil (RT). For most crops, years, and locations, tillage regime did not significantly influence establishment (Table 3.5). There was a tillage regime x crop species interaction at Carman in 2008 and at Notre DL in 2009, where, unlike other crops, pea had significantly higher plant population densities under CT than under RT (77 vs. 61 and 30 vs. 18 plants m^{-2} respectively; Table 3.5). A similar trend was observed for oilseed radish at Notre DL in 2009. Very high levels of fall rye residue may have been responsible for reduced establishment of double crops in RT plots at Notre DL in 2009.

Among double crops, pea consistently produced the highest biomass, ranging from 160 to 2357 kg ha^{-1} and averaging 890 kg ha^{-1} for the 8 site years (Table 3.6). The pea crop failed in only one circumstance. Poor pea establishment in the RT system at Notre DL in 2009, presumably due to excess fall rye residue, resulted in poor establishment (18 plants m^{-2}) and low biomass production (160 kg ha^{-1}) at this site.

No previous studies have investigated biomass production of pea as a late-season cover crop in Canada. When grown as a spring-seeded crop for 8 to 10 weeks in Saskatchewan, pea produced 3008 kg ha^{-1} of biomass (Biederbeck et al. 1993). The growing period from seeding to termination in our experiment was less than 8 weeks in most instances (Table 3.1). More importantly, pea reaches its maximum growth rate at the podding stage. Pea in our experiment rarely reached full bloom (data not shown) and grew under progressively declining temperatures.

As indicated in Table 3.6, lentil biomass production ranged from 120 to 377 kg ha^{-1} over 4 site years and was lower than the 190 to 1051 kg ha^{-1} reported by Thiessen Martens et al. (2001). Hairy vetch produced up to 650 kg ha^{-1} at Carman in 2009 (Table 3.6). Cowpea and soybean failed to produce biomass two and three of four times, respectively. In 2009 at Carman, however, cowpea produced 470 kg ha^{-1} of biomass, perhaps as a result of a warmer than normal September (Table 3.2). Oil seed radish produced less than 100 kg ha^{-1} in all site years. Although the main objectives of this study revolve around N benefit from legume cover crops, oil seed radish was included in the study because of its widespread usage by farmers in NGP. Oil seed radish is particularly suitable in situations where; *i)* soil fertility is high, *ii)* there is a need to produce forage for livestock, and, *iii)* where there are soil compaction issues (Williams and Weil 2004). Therefore, among the double crops tested, pea was the most consistent and highest biomass producer.

The presence of significant tillage regime by cover crop species interactions demonstrated that different cover crops responded to seedbed preparation management differently. For example, at Glenlea in 2008, RT pea produced more biomass than CT pea, while the opposite trend was observed for lentil (Table 3.6). At Carman in 2009, oil seed radish and hairy vetch responded with increased biomass production in CT versus RT, but other cover crops were not affected. Non significant tillage regime x cover crop species interactions were observed at the other two site years where all double crop species were compared. These observations demonstrate no consistent effect of tillage regime on cover crop biomass production.

Pea managed under RT produced significantly more biomass than those managed under CT in 2 of 8 site years (at Glenlea 2008 and 2010), while no differences in pea biomass between CT and RT were observed at 4 of 8 site years (Table 3.6). At Notre DL in 2009 and at Carman in 2010 pea under CT produced more biomass than pea under RT. Working on a loam soil in North Dakota, Carr et al. (2009) observed higher pea yield under no-till compared with tillage at 2 of 6 years, with no difference at the remaining 4 years. Working on sandy and clay loam soils in Manitoba, Borstlap and Entz (1994) observed higher pea biomass at maturity under zero tillage than CT. Both studies concluded that the positive impact of RT on pea productivity is more evident under dry conditions; an observation that did not apply in the present study. As a result of lower temperatures in autumn, late-season seeded cover crops have higher water use efficiencies than spring-seeded crops (Nielsen et al. 2005). Therefore, improved water use efficiency of pea seeded under RT management in spring-seeded situations may not apply in late-season situations.

Relay Crops versus Double Crops

The two most productive late-season cover crop species in this study were red clover and pea. A comparison of the biomass production of these species showed that red clover produced more biomass than RT pea at 4 of 5 site years and red clover produced more biomass than CT pea at 3 of 5 site years (Table 3.6). Only in 1 of 5 site years did red clover produce less biomass than pea. Therefore, the best relay crop (red clover) produced as much or more biomass as the best double crop (pea) in the majority of the cases. However, unlike red clover, which failed 1 out of 6 years to produce biomass, pea consistently produced biomass at all 8 site years. Therefore, despite having less biomass, pea established more consistently than red clover. Since red clover is much lower cost to establish (\$30-60 ha^{-1} at 10 kg ha^{-1} seeding rate) than pea (\$80-100 ha^{-1} at 100 kg ha^{-1} seeding rate), producers may opt for red clover for economic reasons.

Wheat N Uptake, Yield and Protein Response

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

Wheat N Uptake at Stem Elongation

N uptake at wheat stem elongation stage is an important measure of a system's early season N status with implications for yield potential and weed competition (Crews and Peoples 2005). In the present study, cover crop species significantly affected N uptake at 2 of 4 sites (Table 3.7). At Carman in 2009, wheat after pea, hairy vetch and cowpea higher N content than for all other cover crops. Red and sweet clover had not established in the previous year at Carman. At Notre DL, wheat after relay-cropped red and sweet clover took up more N than other plots, including pea. Relay crops at Notre DL had produced significantly more biomass than double crops and this appeared to increase early season N availability to wheat in RT.

Nitrogen benefits of relay-cropped red clover to corn were observed in Michigan and Ontario (Hesterman et al., 1992; Vyn et al. 2000). However, lack of red clover N benefit to canola in Alberta (Blackshaw et al., 2010a), resulted from negligible cover crop biomass production (40 to 90 kg ha^{-1}) of the red clover in those semi-arid conditions. One surprising observation in the present study was the inability of very high legume cover crop biomass (3696 kg ha^{-1}) to raise N uptake in wheat at Glenlea in 2009 (Table 3.7). A possible explanation for the poor N capture may be associated with very wet spring conditions that may have caused denitrification or leaching at this site.

Tillage increased early season N availability at 3 of 4 site years. Wheat at stem elongation in the CT plots took up 7-21 kg ha^{-1} more N than wheat in RT plots (Table 3.7). This finding shows that delaying tillage until spring reduces early season N availability. Reduced early N availability from no-till legumes has been shown by other workers (Varco et al. 1993; Groffman et al. 1987). A recent Manitoba study (Vaisman et al. 2011) showed that compared to CT, reducing tillage operations in organic pea-oat green manure resulted in less available N (38 to 50 % reduction) to the subsequent wheat crop. These authors also observed that N availability did not increase in spring-tilled treatments compared to no-till treatments and concluded that reducing tillage in organic green manure systems significantly reduces N mineralization.

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

Wheat N Uptake at Maturity

Nitrogen uptake at crop maturity is a measure of seasonal N supplying power of the cropping system. In the present study, wheat N uptake at maturity ranged from 12 to 91 kg ha^{-1} (Table 3.7) and was generally lower than that reported in other Manitoba studies on organic wheat production [eg., 95 to 205 kg ha^{-1} and 50 to 81 kg ha^{-1} reported by Vaisman et al. (2011) and Wiens et al. (2006) respectively]. It is plausible that the extremely low N uptake at Notre DL (12 to 29 kg ha^{-1}) resulted from immobilization of N by the very high levels of fall rye residue in the RT treatment.

The overwhelming outcome observed at maturity was that the effect of cover crop species on N uptake of wheat was strongly modified by tillage regime. Significant species by tillage interactions were observed at 3 of 4 site-years (Table 3.7). Only at Carman in 2009 was no significant interaction observed. For most site years, the crop species main effect was not significant at maturity, indicating that there was little difference in N supplying capacity of the different cover crops.

The reasons for significant tillage by cover crop species interactions were different at the different site-years. At Notre DL and Glenlea some cover crops did not produce any biomass (soybean and cowpea). Where no cover crop biomass was produced, reducing tillage usually decreased wheat N uptake (Table 3.7). Where cover crops successfully produced biomass the previous autumn (pea, lentil, clovers and hairy vetch), reducing tillage either did not affect N uptake or increased N uptake. A possible explanation for the interaction is as follows. Where no legume biomass was produced, reducing tillage immobilized N, a process that is well documented (Mulvaney et al. 2010). However, where cover crop legume biomass was produced, the N immobilization effect of RT appears to have been offset by the added legume N. This suggests that when legume biomass is present, fall tillage may be eliminated without negative effects on wheat N uptake in the following year.

A linear regression analysis was conducted (data not shown) to investigate the relationship between legume biomass production and wheat N uptake at stem elongation and maturity. No consistent pattern among site years, as to how much biomass was required to offset the slow mineralization resulting from absence of tillage was observed. Analyzing the N contribution of relay-cropped red clover to corn, Liebman et al. (2012)

found inconsistent response of soil nitrate and corn stalk N concentrations to time of tillage (fall and spring tillage). However they did find a significant positive correlation between corn yield and red clover biomass production. Future research using ^{15}N labeled cover crops can help in determining the fate of cover crop N after incorporation.

Wheat grain yield and protein content

Significant crop species effects for wheat grain yield were observed at Glenlea, Carman 2009 and at Notre DL (Table 3.8). Since the grain yield potential is largely affected by N availability before anthesis (Demotes-Mainard et al. 1999), early season N availability provided by legume biomass (as measured in wheat stem elongation N uptake) was reflected in higher yields. At Carman in 2009, wheat after pea resulted in the greatest yield. It is important to note that there was no red and sweet clover growth at this site year.

Tillage regime had a significant impact on wheat yield at 3 of 4 site years, as wheat grown in CT plots yielded more than wheat grown in RT plots. Perhaps, the lack of adequate biomass production of double crops at Carman in 2008 and 2009 resulted in poorer N supply to wheat in RT plots than CT plots. There were significant crop species x tillage regime interaction effects for yield at Glenlea and Notre DL (Table 3.8). At Glenlea, wheat in the CT control and cowpea plots resulted in greater yields than RT but wheat in all the other crop plots yielded same under both tillage regimes. At Notre DL wheat grown in RT relay crop plots yielded the same as CT ones but for double crops resulted in greater wheat yields under CT. At Notre DL, red and sweet clover biomass production were 2109 and 1259 kg ha^{-1}, while double crop biomass production only reached 570 kg ha^{-1} for CT pea. Thus, once again, the capacity of late-season legume biomass production to offset the slow N mineralization from RT is illustrated.

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

3.5 Conclusions

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

Wheat N uptake and yield increased with increasing relay and double crop biomass production at most site years. Although biomass production and N benefit vary by site and year, low seed cost and seeding rates of red and sweet clovers make them attractive options for low-input organic farmers. Pea is also recommended as it produced acceptable amounts of biomass 6 out of 8 site years. Relay crops in the present experiment appear to provide more N benefit than double crops. Results of this study provided evidence that biomass production by clovers and pea were effective at offsetting reduced tillage-induced N mineralization reduction. Without the legume N from these cover crops, eliminating fall tillage almost always reduced N supply to the following wheat crop. Therefore, this study provided evidence that the presence of a late-season cover may facilitate reduced tillage in organic farming by offsetting the N limitations that occur when fall tillage is eliminated. Further research is needed to establish the amount of critical cover crop biomass needed to reduce tillage in organic late-season cover crop production.

Tables

Table 3.1. Seeding and termination (conventional tilled) dates for relay and double crops from 2008 to 2011 at Carman, Glenlea and Notre Dame de Lourdes (Notre DL).

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

Table 3.2. Average monthly growing season air temperatures, 30-year average air temperatures and monthly growing season GDD (growing degree days) from 2008 to 2011 for Carman, Glenlea and Notre Dame de Lourdes (Notre DL).

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

^{z}from 1971 to 2000 for Glenlea and Notre DL from 1961 to 1990 for Carman (Environment Canada 2013)

Table 3.3. Average growing season monthly precipitation from 2008 to 2011 and the 30 year average for Carman, Glenlea and Notre Dame de Lourdes (Notre DL).

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

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

[y] precipitation information provided by Gerard DeRuyck based on on-farm rain gauge

Table 3.4. Relay crop plant population densities for one date in 2008 and for two dates in 2009 and 2011 at Carman, Glenlea and Notre Dame de Lourdes (Notre DL).

	2008		2009				2011			
	Glenlea	Carman	Carman		Notre DL		Carman		Notre DL	
Relay crop	2-Jun	2-Jun	1-Jun	15-Jun	1-Jun	15-Jun	6-Jun	July 4	6-Jun	12-Jul
	----------	----------	----------	----------	----------Plants m^{-2}----------	----------	----------	----------	----------	----------
Red clover	87	0	34	54	44	84a[z]	64a	85a	35a	99a
Sweet clover	66	0	38	41	59	69b	29b	15b	8b	5b
ANOVA (p > f)	0.189	n/a	0.646	0.333	0.158	0.047	0.049	<0.0001	0.001	0.003

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

Table 3.5. Double crop plant population densities from 2008 to 2011 at Carman, Glenlea and Notre Dame de Lourdes (Notre DL) for pea, hairy vetch, lentil, soybean, cowpea, and oil seed radish managed under reduced tillage and conventional tillage.

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

[z] Crop not seeded

[y] LSD for the effect of double crop is 6 plants m^{-2}

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

[w] LSD for the effect of double crop is 9 plants m^{-2}

Table 3.6. Crop species and tillage regime effect on double and relay crop (red and sweet clover) biomass production from 2008 to 2011 at Carman, Glenlea and Notre Dame de Lourdes (Notre DL) for pea, hairy vetch, lentil, soybean, cowpea, and oil seed radish managed under reduced tillage (RT) and conventional tillage (CT).

	2008		2009		2010		2011	
Treatments	Glenlea	Carman	Carman	Notre DL	Carman	Glenlea	Carman	Notre DL
	kg ha^{-1}							
Reduced tillage								
Pea	850a[z]	978	520ab	160	1463b	905a	928	1320
Hairy vetch	281cd	315	225d	-	-	-	-	-
Lentil	173de	349	287cd	157	-	-	-	-
Soybean	145e	130	0	0	-	-	-	-
Cowpea	0[y]	11	470ab	0	-	-	-	-
Oil seed radish	-[x]	0	57e	67	-	-	-	-
Conventional tillage					-	-	-	-
Pea	534b	753	670a	570	2357a	354b	1303	1011
Hairy vetch	180de	262	650a	-	-	-	-	-
Lentil	314c	330	377bc	120	-	-	-	-
Soybean	142e	119	0	0	-	-	-	-
Cowpea	0	13	594cd	0	-	-	-	-
Oil seed radish	-	0	352ab	52	-	-	-	-
Source of variation	P values							
Crop species (CS)	<.0001	<.0001[w]	<.0001	0.0017[v]	-	-	-	-
Tillage regime (TR)	0.0234	0.1356	0.0043	0.9423	0.0267	0.0430	0.4800	0.1122
CS x TR	0.0009	0.3720	<.0001	0.8982	-	-	-	-
Relay crops								
Red clover	3696	0	850	2109	-	-	4075	737
Sweet clover	1450	0	460	1259	-	-	93	0
Anova (p > f)	0.0002	n/a	0.246	<0.0001	-	-	0.0021	n/a
Contrasts								
Red clover vs. RT Pea	0.0012	-	0.3326	0.0003	-	-	0.0002	0.0133
Red clover vs. CT Pea	0.0007	-	0.9191	0.0016	-	-	0.0003	0.1170

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

[y] not included in ANOVA analysis

[x] Crop not seeded

[w] LSD for the effect of double crop is 181 kg ha^{-1}

[v] LSD for the effect of double crop is 313 kg ha^{-1}

Table 3.7. Wheat N uptake at stem elongation and maturity following reduced tillage (RT) and conventional tillage (CT) red clover, sweet clover , pea, hairy vetch, lentil, soybean, cowpea, and oil seed radish and control at Carman, Glenlea and Notre Dame de Lourdes (Notre DL) Manitoba in 2009 and 2010.

Treatments		Glenlea 2009		Carman 2009		Carman 2010		Notre DL 2010	
Tillage regime	Crop species	Stem elongation	Soft Dough	Stem elongation	Maturity	Stem elongation	Maturity	Stem elongation	Maturity
		-------kg N ha^{-1}-------							
Reduced tillage	Red clover	28	42b[y]	-	-	17	33e	23	27ab
	Sweet clover	34	60a	-	-	24	28e	24	29a
	Pea	29	31bcd	46	58	18	31e	11	16bcd
	Hairy vetch	26	29cd	36	50	24	27e	-	-
	Lentil	23	30cd	38	53	17	28e	13	14cd
	Soybean	25	25d	38	46	27	33e	11	14cd
	Cowpea	23	30bcd	38	52	20	28e	12	16cd
	Oil seed radish	-		32	37	16	28e	12	12d
	Control	22	26d	35	36	18	32e	13	15cd
Conventional tillage									
	Red clover	26	34bcd	-	-	34	38de	30	29a
	Sweet clover	24	34bcd	-	-	35	49bcd	31	23abcd
	Pea	24	37bc	54	80	39	39cde	23	22abcd
	Hairy vetch	22	32bcd	57	91	34	51bcd	-	-
	Lentil	26	33bcd	48	90	43	66a	25	25abc
	Soybean	24	30cd	48	87	23	49bcd	22	26abc
	Cowpea	23	32bcd	53	79	38	52abc	29	29a
	Oil seed radish	-	-	52	88	30	57ab	27	28ab
	Control	26	37bc	53	73	36	55ab	22	26abc
	LSD (Tillage regime)	-	-	10.2	36.2	4.2	-	9.8	-
	LSD (Crop species)	-	-	5.3	-	-	-	4.3	-
Source of variation		-------P values-------							
	Crop species (CS)	0.056	0.0038	0.0414	0.5077	0.566	0.2967	<0.0001	0.0783
	Tillage regime (TR)	0.2535	0.789	0.0214	0.0497	0.0012	0.0112	0.0351	0.2152
	CS x TR	0.2373	0.0148	0.0838	0.6872	0.6543	0.0496	0.3229	0.0254
Contrasts									
Relay crops vs. Double crops		0.0108	<.0001	-	-	0.9303	0.2756	<.0001	0.0027

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

Table 3.8. Wheat yield and grain protein following reduced tilled (RT) and conventional tilled (CT) red clover, sweet clover, pea, hairy vetch, lentil, soybean, cowpea, and oil seed radish and control at Carman, Glenlea and Notre Dame de Lourdes (Notre DL) Manitoba in 2009 and 2010

Treatments		Yield				Grain protein			
		2009		2010		2009		2010	
Tillage regime	Crop species	Glenlea	Carman	Carman	Notre DL	Glenlea	Carman	Carman	Notre DL
		kg ha^{-1}				g N kg^{-1}			
Reduced tillage	Red clover	741ab[z]	-	749	1595ab	135	-	117	121
	Sweet clover	934a	-	943	1486abc	138	-	111	113
	Pea	543bcdef	2118	831	553g	137	117	116	116
	Hairy vetch	389defgh	1733	870	-	134	111	112	-
	Lentil	300gh	1676	677	633g	138	117	111	114
	Soybean	336fgh	1575	790	500g	137	115	115	113
	Cowpea	274h	1718	764	517g	137	116	113	109
	Oil seed radish	-	1409	670	589g	-	114	110	115
	Control	354efgh	1593	811	517g	132	115	111	110
Conventional tillage									
	Red clover	752abc	-	1371	1404ab	146	-	120	115
	Sweet clover	662bc	-	1362	1561a	139	-	121	118
	Pea	571bcde	2929	1411	1328abcd	142	129	122	115
	Hairy vetch	511cdefg	2574	1433	-	141	129	125	-
	Lentil	590bcd	2416	1609	1381abc	137	126	125	119
	Soybean	506cdefg	2602	1389	1072def	138	127	122	119
	Cowpea	503cdefg	2519	1462	1314bcd	138	126	123	115
	Oil seed radish	-	2522	1351	1306bcd	-	130	121	115
	Control	671bc	2390	1362	1148cde	137	125	123	117
	LSD (Tillage regime)	-	571	197	-	-	11.2	9.1	-
	LSD (Crop species)	-	322	-	-	-	-	-	-
Source of variation		P values							
	Crop species (CS)	<0.0001	0.0258	0.6353	<0.0001	0.8500	0.9158	0.8372	0.0587
	Tillage regime (TR)	0.0148	0.0165	0.002	0.0876	0.4120	0.0380	0.0442	0.3200
	CS x TR	0.0363	0.8885	0.1229	<0.0001	0.5176	0.7465	0.2463	0.0774
Contrasts									
Relay crops vs. Double crops		<0.0001	-	0.9393	<.0001	0.3086	-	0.7952	0.0732

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

CHAPTER 4

EFFECTS OF GRAZING TWO GREEN MANURE CROP TYPES IN ORGANIC FARMING SYSTEMS: N SUPPLY AND PRODUCTIVITY OF FOLLOWING GRAIN CROPS

4.1 Abstract

Grazing green manures may improve N availability and productivity in integrated crop-livestock systems. We hypothesized that grazing green manures, compared with standard soil incorporation with tillage, would increase autumn soil profile NO_3-N concentrations and grain yields in subsequent years. Three multiyear experiments were carried out for three years between 2009 and 2011 in Manitoba, Canada. For all three experiments, spring-seeded oat (*Avena sativa* cv. Leggett) and pea/oat (*Avena sativa* /*Pisum sativum* cv. 40-10) green manure crops were grazed with sheep or left ungrazed in year one. Both treatments were soil incorporated with a tandem disk after grazing. Spring wheat (*Triticum aestivum* cv. Waskada) and fall rye (*Secale cereale* cv. Hazlet) test crops were grown in the second and third years, respectively. Biomass production was greater for pea/oat than oat in experiment 1; in experiment 2 pea/oat = oat; and in experiment 3 pea/oat < oat. Grazing utilization of green manure biomass averaged 62% across all treatments and experiments with no utilization differences between crop species. On average, less than 10% of biomass consisted of weeds for both green manures. Soil NO_3-N to 120 cm was significantly greater in grazed than in ungrazed plots, however soil P and K were unaffected. Nitrate content was greater in pea/oat mixture plots for all three experiments at 0-120 cm than oat plots. The absence of a significant management x green

manure type interaction indicated that both crop types responded similarly to grazing. Greater availability of soil NO_3-N after grazing translated into significantly greater crop growth and N uptake in some years, although significant increases in yield of following crops were not observed. Importantly, grazing green manures never negatively affected wheat or rye yield. In conclusion, grazing green manure crops increased N supply for subsequent crop production with no negative yield effects on two subsequent grain crops.

4.2 Introduction

There is renewed interest in annual forages, especially for extending the grazing season and for use by livestock on permanent croplands (McCartney and Fraser, 2010). Ruminants in integrated crop-livestock systems can utilize cash crop residues, annual cover crops (temporary pasture) and long-term pastures (Gardner and Faulkner, 1991). In organic cropping systems, green manures should be grown as a part of the crop rotation to enrich soil with nitrogen (N) (Entz et al., 2001). In short growing season environments, such as western Canada, dedicating the entire growing season to green manures incurs a cash crop opportunity loss. Thiessen Martens and Entz (2011) suggested an integration between green manures and livestock grazing as a way of improving economic returns from the green manure year, however no experiments have tested this system under organic farm management.

Agronomic and environmental impacts of crop-livestock integration have been investigated in various cropping systems: grain-swath grazing systems of North Dakota (Tanaka et al. 2005), wheat-fallow systems of Montana (Hatfield et al., 2007a, 2007b, 2007c; Sainju et al., 2010, 2011), summer grain/winter cover or winter grain/summer cover crop systems of Georgia (Franzluebbers and Stuedemann, 2007, 2008a, 2008b), winter cover crops or cool season pastures of Illinois (Tracy and Zhang, 2008; Tracy and Davis, 2009; Maughan et al., 2009), winter cover crop, corn silage systems of Ohio (Fae et al., 2009), sod-peanut-cotton systems of Florida and Alabama (Katsvairo et al., 2007), cotton-forage systems of Texas (Allen et al., 2008; Acosta-Martinez et al., 2010). These studies highlight successful integration of both cattle (*Bos taurus*) and sheep (*Ovis aries*) into various cropping systems managed under different ecoregions in the USA. In Canada, a few researchers have reviewed the potential role of integrated crop-livestock systems (Entz et al., 2002; McCartney and Fraser, 2010; Thiessen Martens and Entz, 2011), but no original research has been published.

In integrated crop-livestock systems, plant, animal and soil productivity depend on a number of factors including, but not limited to, plant nutritional composition, developmental stage, morphology, biomass production, herbivore species, age and physiological state, and most importantly grazing intensity (Carvalho et al., 2010). Hence, selection of compatible ruminant and plant species that are adaptable to local edaphic and climatic conditions should precede other considerations when designing integrated crop-livestock systems (Ledgard, 2001). However, most integrated crop-livestock system experiments compare different cropping systems (i.e. a rotation with grazing vs. grain monoculture or pasture), not the crop species within a cropping system. Information regarding establishment, growth and nutritional value of a number of forage species is available (Fraser et al., 2004; McCartney and Fraser, 2010), but most of the reported plant species have been tested under permanent pastures, hay or swath grazing systems. By contrast, little information on weed competitiveness and utilization rate of potential annual green manure species is available. Such information is critical particularly in organic systems, where soil management history may produce different soil fertility levels (van Diepeningen et al., 2006) and weed pressure (Ryan et al., 2010) compared to conventional systems.

There is also limited information regarding the environmental impact (i.e. nitrate leaching potential) of grazing in integrated crop-livestock systems, as well as subsequent crop nutrient uptake, biomass production and yield. To be considered effective, integrated systems must at least maintain the productivity of alternative, less diverse systems and have no negative environmental impact from excessive nutrient availability. Studies using labelled ^{15}N showed that N losses and crop recovery from sheep manure (urine + faeces) were similar to losses and recovery from synthetic fertilizers when applied at similar rates (Thomsen et al., 1997; Bosshard et al., 2009). However, urine N may be lost to leaching when deposited at rates exceeding plant uptake (Stout, 2003; McGechan and Topp, 2004).

Most nutrients (i.e. N, P. K) ingested by ruminants are returned to the soil in excreta, but the amount of nutrients retained and returned is directly influenced by plant nutritional composition and overall diet of the animal (Duncan and Poppi, 2008). Thus, subsequent crop response to grazing is mainly a function of green manure species productivity and nutritional composition. In general, N contained in plant material can be partitioned by ruminants into metabolizable N (3-15%) and plant available N (85-95%) in faecal output, but considerable variation exists in the N, P and K cycles depending on the system and region (Whitehead, 2000).

Phosphorus deficiency in organic systems is well-documented (Cornish, 2009; Welsh et al., 2009). Livestock integration in organic systems has been suggested as a means to recycle and transfer P from plant material to rumen and back to the soil in more plant available forms. Faecal matter decomposition studies have shown that grazing increases plant-available soil inorganic P (Aarons et al., 2004). Plant biomass contains less inorganic P than faecal material (i.e. rumen digested plant biomass), and plant uptake of faecal derived P can be as effective as synthetic P fertilizers (Williams and Haynes, 1995). Potassium in organic systems is also a limiting nutrient, and plant demand for K increases with increasing availability of N (Kayser and Isselstein, 2005). Most of the K is excreted in urine and little is known of the fate of K in urine patches. In grazed grasslands, productivity and K uptake by plants increase around urine patches with high K concentrations (Kayser and Isselstein, 2005).

Objectives of this experiment were to investigate; i) productivity, herbivore consumption and weed competitiveness of oat and pea/oat green manures as potential annual forages, ii) effects of grazing on soil NO_3-N, P (Olsen) and K concentrations, and iii) effects of grazing on biomass production, N uptake and yield of subsequent spring wheat and fall rye crops. We hypothesized that productivity, herbivore consumption and weed competitiveness will be significantly greater for pea/oat green manure than oat green manure. Consequently, grazed pea/oat plots will contain greater amount of soil NO_3-N than grazed oat plots. We also hypothesized that soil NO_3-N, P and K levels will be greater when green manures are grazed than when they are left ungrazed. This difference, in turn, will be reflected in increased wheat and fall rye N uptake, biomass and yields in grazed treatments.

4.3 Materials and Methods

Site description and experimental design

Experiments were conducted at the University of Manitoba Ian N. Morrison Research Farm in Carman, Manitoba (49°29′48″ N, 98°2′ 26″ W, 267 m above sea level). The region is characterized by an extreme continental climate with very cold winters and warm summers. Frost-free period for crop production is 115-125 days, and occurs primarily between May and September (MASC, 2013). Long-term average temperatures, precipitation, as well as 2009-2012 growing season monthly temperatures and precipitation are provided in Table 4.1. Soils at Carman are well drained Orthic Black Chernozems with a fine sandy loam texture (Mills and Haluschak, 1993). Two meters deep clay substrate underlies the soils, which are lacustrine and deltaic sediments with slope of less than 1%, pH of 6.2, and an organic matter content of 25 g kg^{-1}. In the spring of 2009 and 2010 soil background nutrient samples were collected at 0-30 cm for experiments 2 and 3 respectively. Soil NO_3-N, P (Olsen) and K levels in experiment 2 were 11, 20 and 569 kg ha^{-1}, and in experiment 3 were 13, 17 and 477 kg ha^{-1}, respectively. No background soil samples were collected for the experiment 1. Oat was the preceding crop for all experiments. Previous investigations of integrated crop-livestock systems have been exclusively conducted under conventional management with fertilizer inputs. The present study was conducted under long term organic management (since 2004) with no external inputs.

The experimental design was a split-plot design, with four blocks (replications). The whole-plot treatment was green manure species, and the sub-plot treatment was green manure management. Two green manure species (pea/oat and oat) and two green manure management systems (grazed and incorporated) were included. Green manures were incorporated into soil with tandem disk, which is a common practice in this region. The grazing green manures experiment started with an experiment in 2009 (Experiment 1) and was repeated in 2010 (Experiment 2) and 2011 (Experiment 3) on neighboring sites within the experimental station. Table 4.2 shows the field operations and dates for all three experiments. In the first year of each of the experiments, green manures were seeded in the spring, and grazed or incorporated in mid- to late-summer. Both grazed and ungrazed plots were tandem-disked at the same time upon completion of grazing. In the second year, a spring wheat crop was seeded in May on the grazed and incorporated green manure plots. In the third year, a fall rye crop was grown. Experiment 1 and experiment 2 included all three phases of the experiment, but experiment 3 included only two phases (green manure year and spring wheat year).

Spring wheat establishment in experiment 2 failed as a result of higher than normal precipitation in fall 2010 and spring 2011. Spring wheat contained more than 60% weed biomass, therefore was incorporated into soil at stem elongation stage. Redroot pigweed (*Amaranthus retroflexus)* grew over these plots comprising more than 90% of the plant biomass. Therefore, the decision was made to consider redroot pigweed biomass as the test crop in place of wheat.

Green manure species and management

The pea/oat mixture was seeded at 50 kg ha^{-1} of oat (*Avena sativa* cv. Leggett) and 100 kg ha^{-1} of pea (*Pisum sativum* cv. 40-10). The seeding rate for oat alone was 120 kg ha^{-1}.

Both green manures were seeded using a JT-A10 air drill seeder (R-Tech Industries Ltd. Homewood, MB) with a row spacing of 20 cm. Timing for grazing green manures depended on the amount of biomass production and generally coincided with the full-bloom stage for pea and milk stage for oat. Pea was inoculated with the appropriate *Rhizobium* species; NitraStic-C peat based inoculant (Novozymes, Franklinton, NC). Inoculant was applied at the manufacturer's recommended application rate of 75 mL of inoculant per 27 kg of seed.

Stocking density was determined based on available green manure biomass and the ewes' dietary requirements based on their physiological stage. Average weight of the ewes and lambs were approximately 70 and 30 kg respectively. Daily nutrient requirements of the ewes were assumed to be from 2% of the body weight for dry ewes to 3.5% of body weight for lactating ewes with one lamb (NRC, 1985a). Therefore, stocking density per plot ranged from 2 to 3 ewes (South African Dorper) and 2 to 5 lambs for 24 h (1111 to 1667 sheep d/ha).

Sheep were put into conditioning plots containing each green manure crop for 24h before they were put into actual experimental plots. As such, sheep started to consume the green manure species being tested a day before they were put into actual plots. This one-day conditioning assumed that sheep excreted the green manure biomass consumed 1 day before, and rate of passage of green manure was around 24h. While there is evidence in the literature to support this assumption (Mertens and Ely, 1979; Uden et al., 1982), residence time of feed in the rumen can be longer than 24h (NRC, 1985b). Since the animal weight gain or other productivity measures were not investigated in the current study, we relied on the shorter duration passage rate (i.e., 24h) for our purposes.

Sub-plots were 2 m wide and 9 m long and were surrounded by metal fences for precision and protection. Water buckets and shade tents were positioned in opposite ends of the plots to prevent uneven nutrient distribution. Since each green manure reached the full-bloom stage at different dates, sheep grazed each green manure species at different times. When a species were ready for grazing, at least two of the replicates were grazed simultaneously. As such, grazing of one species did not exceed more than 2 days, which assured that similar forage quality material were being fed to ewes. A blade-roller was used to terminate the ungrazed side of the green manure plots as soon as the sheep started grazing. Blade roller equipment is able to kill green manures by crimping action (Vaisman et al., 2011).

Following green manure grazing in the first year, spring wheat (*Triticum aestivum* cv. Waskada) was seeded in the second year as a first test crop. Fall rye (*Secale cereale* cv. Hazlet) was seeded after wheat harvest in the autumn as a second test crop. Spring wheat and fall rye were also seeded using a JT-A10 air drill seeder with a seeding rate of 125 kg ha^{-1} and 110 kg ha^{-1}, respectively.

Soil sampling

Soil samples were collected in October (i.e., end of growing season and beginning of winter) for each phase of the experiments. Only in the second year of experiment 2, were samples collected in the following spring (May 2011, before seeding spring wheat) instead of October 2011. Soil samples were collected using Dutch augers in 2009 and 2010, and using a hydraulic soil-coring rig (The Giddings Machine Co, Windsor, CO, USA) with a 4-cm diameter tip in 2011 and 2012. Composite soil samples were taken at two spots in each plot to 120 cm depth, at four depth increments; 0-30, 30-60, 60-90 and 90-120 cm. All soil samples were sent to Agvise commercial soil analysis laboratory for chemical analysis (AGVISE, Northwood, ND). Soil samples were analyzed for nitrate (NO_3-N) at all four depths using the cadmium reduction method, for plant available soil P at 0-30 cm depth using 0.5 M $NaHCO_3$ (P Olsen), and for soil K at 0-30 cm depth using 1 M $NH_4C_2H_3O_2$ extraction. Soil pH was determined with pH electrode in a 1:1 soil:water suspension. Soil organic matter was determined by loss of weight on ignition at 360^{o}C.

Plant sampling

Green manure above-ground biomass production in year 1 was determined by clipping 2 x 0.4 m^2 randomly chosen samples from each of the four experimental units before grazing. Utilization was calculated as the percentage of forage dry matter consumed by sheep. Percent forage utilization by grazing was determined by taking residual above-ground biomass (2 x 0.4 m^2) from grazed plots within 3 days of the end of the grazing period. This biomass was washed (to eliminate soil and faeces adhering to residual biomass) and dried for 48 h at 60 ^{o}C, then weighed for dry matter content. For experiment 1, post-grazing residual biomass was not washed before drying and weighing, which may have caused the overestimation of amount of residual biomass. For the experiments 2 and 3, when conditions were much wetter during grazing, soil had to be washed off of residual plant material in order to get accurate plant biomass.

Weed biomass was determined by hand-sorting green manures and by weighing weeds after drying for 48 h at 60 ^{o}C. Common weed species were Canada fleabane (*Conyza canadensis*), barnyard grass (*Echinochloa crus-galli*), lamb's quarters (*Chenopodium album*), redroot pigweed (*Amaranthus retroflexus*), yellow foxtail (*Setaria glauca*), green foxtail (*Setaria viridis*), shepherd's-purse (*Capsella bursa-pastoris*), wild buckwheat (*Polygonum convolvulus*), lady's thumb (*Polygonum persicaria*), Canada thistle (*Cirsium arvense*), quackgrass (*Elymus repens*), and dandelion (*Taraxacum officinale*).

Spring wheat and fall rye biomass samples were harvested at the soft dough stage from 2 x 0.4 m^2 areas in each experimental unit, dried for 48 h at 60 ^{o}C and weighed. In the year when redroot pigweed served as the test crop, plant biomass was collected from 2 x 0.5 m^2 areas in each experimental unit, dried for 48 h at 60 ^{o}C and weighed. Spring wheat and fall rye grain for yield estimation were collected from each plot using a Kincaid 8-XP (Kincaid Equipment Manufacturing, Haven, KS) plot harvester. Dry wheat and fall rye biomass samples were ground with a Wiley Mill (No.1 Arthur H. Thomas Co., Philadelphia, PA). Wheat and fall rye grains were ground with a Cyclone Lab Sample Mill (UDY Corporation, Fort Collins, CO). All ground samples were subsampled and analyzed for N concentration by combustion analysis using a LECO FP-528 (LECO, St. Joseph, MI). Wheat and fall rye N uptake at soft dough were calculated as the product of above-ground biomass production (kg ha^{-1}) and its N concentration.

Total plant available N

Soil NH_4-N concentration was assumed to represent less than 5% of the total soil N stocks (Xu et al., 2013). Therefore, total plant available N supply from green manures was calculated as the sum of residual soil NO_3-N (fall rye year autumn soil NO_3-N) and plant material N concentration (wheat and fall rye soft dough biomass) using the following formula;

Total plant available N supply = residual soil NO_3-N + wheat biomass N + fall rye biomass N

Statistical analysis

Statistical Analysis System program (SAS Institute, 2001) PROC MIXED procedure was used for data analysis. We used ANOVA and considered treatment effects as fixed effects and replications as random effects for all measurements. For green manure biomass productivity, weed competition and utilization, green manures species and experiments were fixed effects and the replications were random. For total N uptake analysis, green manure species, management and the experiments were the fixed effects. Assumptions of ANOVA were tested by using the PROC UNIVARIATE procedure. All data were verified for normality of residuals and homogeneity of variance. Differences were considered significant at $p < 0.05$ and means were separated using a Fisher's protected LSD test.

4.4 Results

Green manure productivity and utilization

Green manure aboveground biomass production varied across experiments (Figure 4.1), responding to precipitation patterns. Greatest biomass production of pea/oat was in experiment 1 (6157 kg ha^{-1}) and lowest in experiment 3 (3352 kg ha^{-1}). Both green manure types produced high levels of biomass in experiment 2 (Figure 4.1). For experiment 1, biomass production of pea/oat was greater than that of oat. For experiment 2, biomass production of pea/oat equaled that of oat; whereas for experiment 3, pea/oat biomass production was lower than that of oat.

The lack of significant green manure species and experiment effects for weed biomass (Table 4.3) suggest that weed competitiveness of green manures was consistent across treatments. Weed pressure was low across green manure species and experiments and ranged from 5 to 15% (Table 4.3 and Figure 4.1). Weed pressure at time of grazing averaged 10 and 7% of total aboveground biomass production for pea/oat and oat, respectively for all three years.

Utilization as the amount of biomass consumed by grazing sheep ranged from 45 to 74% (Figure 4.1). Utilization was similar ($p > 0.05$) between green manure types, however, it varied among experiments.

Soil nitrate, phosphorus and potassium

Soil nutrients after green manure grazing and incorporation (year 1)

Soil NO_3-N was measured after green manure grazing (in autumn) to determine whether grazing increased the short-term N availability in the 0 to 120 cm soil profile. Total soil NO_3-N was significantly greater in grazed compared with ungrazed plots in the first year of all three experiments (Table 4.4, Figure 4.2). Similarly, total profile soil NO_3-N level in pea/oat plots was greater than in oat plots in all three experiments.

Distribution of NO_3-N in the 120 cm soil profile allowed us to determine whether grazing increased leaching potential of NO_3-N. By the end of year 1, most NO_3-N had accumulated in the top 30 cm soil. Soil NO_3-N concentration ranged from 22 kg ha^{-1} in ungrazed oat plots in experiment 3 to 138 kg ha^{-1} in grazed pea/oat plots in experiment 1 (Figure 4.2). Species and management effects were significant for 0-30 cm soil layer in two of three experiments (experiments 1and 3). In all three experiments, NO_3-N levels in the 0-30 cm soil zone were greater in pea/oat vs. oat plots (not significant in experiment 2) (Figure 4.2). The effect of grazing was also consistent among experiments. In all three experiments, NO_3-N levels were greater in grazed compared with ungrazed plots (not significant in experiment 2). Grazing increased NO_3-N in the 0-30 cm soil zone by 36% in experiment 1, 23% in experiment 2 and 22% in experiment 3.

Fewer differences between treatments were observed at soil depths below 30 cm (Figure 4.2). No significant effects of either grazing or green manure type were observed below the 30 cm soil depth after the green manure year. While there was a trend for higher levels of soil P and K with grazing, no significant effect of grazing was observed (Figure 4.3).

Soil nutrients after wheat and fall rye (year 2 and 3)

By the end of the first test crop year (wheat), no significant species or management effects were detected in any of the three experiments (Figure 4.2). As expected, available soil N declined from the end of the green manure year (the N build-up phase) to the end of the first extractive crop (i.e., wheat year). The sharpest decline in total soil NO_3-N from the first to the second year occurred in experiment 1, especially in the grazed pea/oat plots (226 to 54 kg ha^{-1}). Soil P content in the second year was not affected by species or management and ranged from 13 kg ha^{-1} in experiment 3 to 40 kg ha^{-1} in experiment 1. Similarly, soil K content was also not affected by species or management. Soil P levels in the second year declined relative to first year levels, for all experiments.

By the end of the fall rye year (i.e. after fall rye grain harvest), NO_3-N levels remaining in the soil were very low and no significant effects were detected. Similarly, no differences in soil P or K concentrations were observed after two extractive crops following the green manure year.

Wheat and fall rye N uptake and productivity

Wheat productivity varied among experiments and maybe attributed to variation in precipitation across years (Table 4.1). Growing season precipitation was above long-term average in 2010, but was below average in 2012. Wheat responded to precipitation patterns, producing high above-ground biomass and yield in normal rainfall and wet years, but low above-ground biomass and yield in the dry year.

Wheat above-ground biomass production at soft dough stage was affected by green manure species ($p = 0.05$) and management ($p = 0.04$) only in experiment 1 (Table 4.5). Wheat following pea/oat produced greater biomass (11536 kg ha^{-1}) than wheat following oat (9726 kg ha^{-1}) in experiment 1. In the same experiment, wheat following grazing produced greater biomass (11238 kg ha^{-1}) than when green manure was not grazed (10026 kg ha^{-1}). In experiment 2, redroot pigweed biomass production was uniform across treatments. Similarly, no significant treatment effects were observed in experiment

3 for wheat biomass at soft dough. Wheat N uptake at soft dough stage was affected by species in experiment 1 and 2 and by management in experiment 3. Plant N uptake was greater in pea/oat plots than in oat plots for experiment 1 (wheat: 69 vs. 40 kg ha^{-1}) and experiment 2 (redroot pigweed: 64 vs. 44 kg ha^{-1}). Wheat N uptake in grazed green manure plots of experiment 3 was greater (80 kg ha^{-1}) than ungrazed green manure plots (51 kg ha^{-1}).

Wheat yields were greater in pea/oat plots than in oat plots in experiment 1, but there were no differences between treatments for wheat yield in experiment 3. There was a significant species effect in experiment 1, in which wheat grain protein concentration was greater in pea/oat plots (159 g kg^{-1}) than in oat plots (136 g kg^{-1}).

Fall rye above-ground biomass production and N uptake were significantly greater in pea/oat plots than oat plots for experiment 1 (Table 4.6). For all other parameters measured in experiments 1 and 2, there were no significant effects or interaction effects. Management did not alter any of the fall rye productivity parameters measured in this study.

Total N supply

Crop N supply was determined by adding N uptake in wheat and fall rye crops combined across experiments 1 and 2. There was a significant species x experiment interaction effect. Biomass grown in the experiment 1 pea/oat plots contained the greatest amount of N (197 kg ha^{-1}). Biomass grown in pea/oat in the experiment 2 and oat plots in the experiment 1 contained similar amount of N (90 vs. 114 kg ha^{-1}). The lowest amount of biomass N uptake was in oat plots in the experiment 2 (66 kg ha^{-1}). The biomass N uptake difference between the pea/oat and oat plots was much higher in the experiment 1 than the experiment 2. Residual soil N did not differ between species and management across the experiments but was significantly higher in the experiment 1 than the experiment 2; 24 vs. 13 kg ha^{-1}.

Total N supply was determined by adding crop N uptake and residual soil NO_3-N after fall rye harvest. There were significant species x experiment and management x experiment interactions for total plant available N (Table 4.7). For experiment 1, pea/oat plots supplied the highest (218 kg ha^{-1}) amount of N, followed by oat (140 kg ha^{-1}). For experiment 2, there were no significant differences between pea/oat and oat plots. Similarly, grazed plots in experiment 1 supplied greater amounts of N than incorporated plots (190 vs. 171 kg ha^{-1}), but in experiment 2 there were no differences between the management systems.

4. 5 Discussion

Performance of oat and pea/oat green manures

The pea/oat green manure mixture was included in this study because it is commonly used by organic farmers in western Canada. Our pea/oat yields (average 5032 kg ha^{-1}) were similar to other reports from Manitoba (5800 kg ha^{-1}) (Vaisman et al., 2011) and Alberta (6100 kg ha^{-1}) (Berkenkamp and Meeres, 1987). The proportion of pea in the mixture ranged from 38 to 51 % (data not shown) and was similar to 44% reported by Berkenkamp and Meeres, (1987).

Oat was included in this study to provide a non-N fixing green manure comparison. Oat is also a suitable grazing crop and a nurse crop for legumes. Oat has been recommended for annual pastures by McCartney et al., (2008). Average oat dry matter yield in this study was 4941 kg ha^{-1}. McCartney et al., (2008) reported oat yields in western Canada ranging from 2110 kg ha^{-1} to 8000 kg ha^{-1}.

Weed control in organic systems is among the major management challenges (Teasdale et al., 2007). Weed suppressing abilities of various annual forages have been previously reported (Schoofs and Entz, 2000; Tracy and Davis, 2009). In this study there were no significant differences between pea/oat and oat green manure crops in terms of weed competitiveness. It is noteworthy that both green manure crops competed with weeds effectively and produced high forage yields under organic management.

Sheep utilization of pea/oat and oat green manure crops was not affected by green manure species. Post grazing residual biomass was similar between green manure types and across experiments (ranged from 1248 to 3488 kg ha^{-1}). Greater post grazing residual biomass (3488 kg ha^{-1}) in pea/oat plots in experiment 1, which resulted in lower utilization rates of both green manure types, may have been due to an overestimation (i.e. soil and faeces adhering to residual biomass) of residual biomass.

McCartney and Fraser, (2010) reviewed studies using pea in mixtures with grasses for winter swath grazing. They concluded that pea/grass mixtures had slightly greater crude protein content but other nutritional properties were similar to monoculture grasses. High protein content is important for intensive grazing operations but may have negative implications in terms of N losses from the system (i.e. nitrification, volatilization and leaching; reviewed in Thiessen Martens and Entz, 2011). Hence in conventional high-N-input systems, a pea/oat mixture offers little advantage over oat and the lower cost of establishing oat makes it more attractive option as an annual forage crop. In organic systems legumes are essential components of green manure systems for N fixation.

Grazing effect on soil nutrient availability

Grazing green manures increased soil NO_3-N content regardless of green manure species used. In the absence of grazing, rate of N release from green manures is mainly a function of residue placement (Mohr et al., 1998a, 1998b; Vaisman et al., 2011). For instance, soil incorporated green manures released N faster than herbicide terminated (Mohr et al., 1999) or surface-mulched green manures (Vaisman et al., 2011). Faster N mineralization from soil incorporated green manure biomass has been attributed to greater contact with soil microorganisms. An advantage of an integrated crop-livestock system is that additional processes (i.e., rumen function) can be brought to bear on decomposition of green manures. Russelle (1992) determined that microbial decomposition of green manure material in the rumen is more efficient than soil microbial decomposition. Results from the present study appear to support this conclusion.

Our observation of greater soil N with grazing is not unique (Tracy and Zhang, 2008; Maughan et al., 2009), although it has not been previously described in annual green manure systems under organic management. However, grazing may not always increase soil N content, as with sheep grazing low N content cereal crop residues (Hatfield et al., 2007b; Sainju et al., 2010). One of our objectives was to compare N availability of grazed legume vs. non-legume green manures. This is an important question given that N is one of the most limiting nutrients in organic production (Berry et al., 2002); legume green manures are critical for bringing N to the system (Cherr et al., 2006). As expected (Biederbeck et al., 1996), soil NO_3-N content in pea/oat plots was greater than in oat monocrop plots. However, no significant green manure species x management interaction was observed for soil NO_3-N. Therefore, this study showed little evidence of a differential response of pea/oat and oat monocrops to sheep grazing. Kyvsgaard et al., (2000) showed that N concentration of faeces was highly correlated with C:N ratio and apparent digestibility of the feed. Carbon:N ratio of green manures was not measured in the present study but should be considered in future research.

Although we did not directly measure N leaching, no evidence of NO_3-N accumulation in the deeper soil layers (i.e. 90-120 cm) was observed compared to upper layers (i.e. 0-60cm). Most of the NO_3-N increases from grazing accumulated in the 0-30 cm soil layer, although in two experiments (2 and 3), treatment differences for NO_3-N were also detected in the 30-60 cm soil layer. Therefore, it appears that the wheat and fall rye crops captured most of the available soil NO_3-N. For instance, soil NO_3-N content of grazed pea/oat plots was 226, 132 and 82 kg ha^{-1} in the first autumn of experiments 1, 2 and 3, respectively. After accounting for wheat N uptake and post-wheat harvest soil residual N, only 28 and 5 kg ha^{-1} of soil NO_3-N was not accounted for in experiments 1 and 2, respectively. Conversely, the sum of wheat N uptake and soil residual N in experiment 3 grazed plots was 22 kg ha^{-1} greater than apparent available soil NO_3-N. Since the unaccounted 28 kg ha^{-1} of N in experiment 1 was not detectable at deeper soil depths, an assumption can be made that N was not lost through leaching, but may have been lost via gaseous emission or transformation into soil mineral structures or organic matter fractions.

Potential gaseous N loss pathways such as volatilization and denitrification were not investigated in this study. However, working with a pea/oat green manure in the same location, Vaisman et al., (2011) showed that ammonia volatilization losses were less than 2% of total biomass N from incorporated pea/oat green manures and 8% from surface placed rolled mulch. Soil incorporation reduces volatile N losses and this may contribute to greater available N supply (Janzen and McGinn, 1991; Mohr et al., 1998b). Volatilization in grazing systems occurs as a result of urea hydrolysis, leading to ammonia gas losses of 15-25% within a few days of urea excretion from the animal (Haynes and Williams, 1993). Since grazed plots in the present study were soil incorporated one or two days after grazing, some potential for volatile N losses did exist. Gaseous N losses in organic, grazed, legume-based, grazing systems require additional research.

Results for P and K showed no increase in soil content due to grazing. Other short-term grazing studies have reported similar results (Hatfield et al., 2007b), although no previous studies have considered the type of system that we tested here, i.e., a green manure N supply crop in an organic cropping system. With initially high soil P and K levels and using P and K fertilizers, Carvalho et al., (2010) showed that soil P levels increased in both grazed and ungrazed treatments over 6 years, but K levels decreased in grazed treatments. Other studies that assessed P and K cycling in pastures with cattle, sheep and deer faeces have shown increased plant available P availability in soils under the faeces

(Bromfield and Jones, 1970; Williams and Haynes, 1995; Aarons et al., 2004; Kayser and Isselstein, 2005).

Wheat and fall rye productivity and nitrogen uptake

Benefits of single-year legume green manure production to following crops are well known (Drinkwater et al., 2000). The response of following crops is related to the amount of N-rich biomass produced (Bullied et al., 2002) and the intensity of soil incorporation (Vaisman et al., 2011). Since most of the N in incorporated green manure is in organic form (Janzen et al., 1990), we hypothesized that grazing would provide additional "processing" of the green manure plant material that would result in greater N availability to following crops. Nitrogen is mainly excreted through urine, which is converted to plant available NO_3-N upon deposition to soil (Haynes and Williams, 1993). We found greater N availability in grazed compared with ungrazed treatments. Grazing also increased wheat productivity in terms of greater soft dough biomass production (experiment 1) and soft dough N uptake (experiment 3) in some cases.

It was notable that no negative effects of grazing on wheat productivity parameters were observed in this study; all parameters of wheat productivity following grazing were greater than or equal to ungrazed plots.

Literature regarding the effect of grazing single-year green manures on following year crops, especially in the Northern Great Plains, is scarce. No previous studies have compared grazing a single-year green manure crop. Some previous research in our region has focussed on grazing crop residues (eg., Sainju et al., (2010). Tanaka et al.,

(2005) observed that winter swath grazing of crop residues in North Dakota resulted in greater forage and grain production compared to systems without grazing. In Illinois, corn yield was greater in grazed winter cover crop systems than continuous corn (Maughan et al., 2009). In Georgia, wheat stover production was greater after grazing of summer cover crops under both conventional and no tillage (Franzluebbers and Studemann, 2007). In Southern Brazil, Carvalho et al., (2010) showed that grazing maintained crop yields under no-till system. They concluded that rumen processing of the additional surface plant material under no-till improved nutrient cycling. Organic systems rely heavily on tillage to control weeds and facilitate mineralization of crop residues (Peigné et al., 2007; Vaisman et al., 2011). Clearly there is a need to establish whether grazing can be used in organic systems to reduce tillage intensity.

The only grain quality parameter assessed here was grain protein concentration. Overall, grain protein levels were high; the Canadian market pays a premium for wheat with greater than 130 g kg^{-1} of protein. We detected a significant species effect on grain protein in only one experiment (experiment 1), in which grain protein concentration in pea/oat plots (159 g kg^{-1}) was greater than in oat plots (136 g kg^{-1}). This result appeared to be due to greater soil NO_3-N content in pea/oat plots (184 vs. 103 kg ha^{-1}) the previous autumn. However, grazing effects on grain protein concentration were absent, despite greater soil NO_3-N content in the year previous to wheat. Similar protein levels under both management systems with different amount of available N, may be explained by the classic “protein dilution” effect (Entz and Fowler, 1989). Greater early availability of soil NO_3-N in the grazed system increased early season N availability and subsequent biomass production compared to the ungrazed plots. The extra N from grazing was translated into greater grain yield, thereby diluting the additional N.

We hypothesized that the N benefit from grazing would extend to the second grain crop following the green manure year. Therefore, fall rye was included in this experiment. However, no grazing effects or grazing by species interactions were detected in our study. The only significant effect was greater fall rye soft dough biomass and N uptake in pea/oat compared with the oat monoculture. Bullied et al., (2002) also observed greater N uptake in the second crop after green manure when the green manure contained higher levels of N. Therefore, our results indicated that including a higher N content green manure is more important to second year N availability whether or not the green manure is initially grazed. Our hypothesis that grazing will provide N benefit to a second grain crop after green manuring was rejected.

Total N supply

Total crop N uptake was similar between grazed and ungrazed treatments. This means that consumption, transformation and small amount of removal of nutrients by grazing animals did not reduce N availability to following crops. However, total plant available N (crop N uptake + soil nitrate) was greater in grazed than ungrazed treatments.

Interaction between experiment and grazing management provided an opportunity to evaluate the robustness of the grazing effect. This analysis, which was only possible for experiments 1 and 2, revealed that grazed plots provided more N to the system in experiment 1 but not in experiment 2 (Table 4.7). At the end of the green manure year in experiment 2, soil NO_3-N level was 108 kg ha^{-1} in grazed plots but only 83 kg ha^{-1} in ungrazed plots. Why did this additional N not increase productivity the following year? One possible reason may have been excess soil water during the wheat year in experiment 2 (Table 4.1). In fact, it was this excess water that killed wheat and forced us to use redroot pigweed as the N bioassay crop. In addition to killing wheat, soil water saturation may have also increased denitrification losses.

4.6 Summary and Conclusions

Both green manure types tested in this study produced acceptable levels of biomass, competed with weeds and were readily utilized by sheep. Therefore, this study confirmed the forage potential of pea/oat and oat for organic systems. A novel experimental approach was used to integrate grazing animals into these agronomic studies combining a standard agronomic small plot design with grazing animals. This experimental approach was successful.

At the end of the green manure year, available soil N was always greater in grazed compared with ungrazed plots. Therefore, one consistent conclusion of this study was that grazing increased soil NO_3-N. While soil in pea/oat plots experienced greater accumulation of NO_3-N than soil in oat plots, the magnitude of increase in available N due to grazing was sometimes greater in oat than in pea/oat green manure. More research is needed to evaluate strategic grazing for increasing bioavailability of N for non-legume green manures. For example, organic farmers are gaining confidence growing novel green manure cover crops such as forage radish (*Raphanus sativus*). How will grazing affect bioavailability of N in these non-legumes?

Greater amount of available soil N brought about by grazing green manures sometimes increased growth and N uptake in following grain crops, but results were not consistent across experiments. However, no negative effects of grazing were observed on the growth and yield of the two grain crops that followed the green manure year. Based on these observations, we conclude that grazing green manures can be economically attractive since animal live weight gain may be achieved in the green manure year without sacrificing N benefit to crops later in the rotation. However, grazing requires additional labour, which is a limited resource in western Canada.

Tables and Figures

Table 4.1. Average monthly growing season air temperatures and precipitation for Carman, Manitoba, Canada from 2009 to 2012.

	Air temperature (^oC)					Precipitation (mm)				
Month	2009	2010	2011	2012	30-year average[a]	2009	2010	2011	2012	30-year average[a]
April	2.9	8.7	4.5	6.2	4.2	23	35	44	19	42.5
May	8.5	11.6	10.4	12.1	12.5	74	159	72	61	52.7
June	15.4	16.3	16.7	17.7	16.9	127	63	59	86	72.8
July	16.9	19.6	20.3	21.9	19.4	62	48	38	28	69.1
August	17.1	18.7	19.3	19.0	18.2	53	138	12	47	65.5
September	17.3	11.8	14.0	12.5	12.2	18	107	65	3	49.0
October	3.6	8.3	8.2	4.2	5.5	28	57	8	85	34.0
Total (April-Oct.)						385	607	298	329	385

[a] from 1961 to 1990

Table 4.2. Dates of field operations for experiments 1, 2 and 3.

Experiment	Seed green manure	Graze green manures	Green manure incorporation	Wheat seeding	Wheat harvest	Fall rye seeding	Fall rye harvest
1	June 1, 2009	July 20, 2009	July 21, 2009	April 23, 2010	Aug 25, 2010	Sept 7, 2010	Aug 18, 2011
2	May 27, 2010	July 19, 2010	July 20, 2010	May 20, 2011	Aug18, 2011[a]	Sept 14, 2011	July 31, 2012
3	May 19, 2011	July 20, 2011	July 21, 2011	April 26, 2012	Aug 9, 2012	-[b]	-

a Wheat failed. Redroot pigweed biomass harvest

b Fall rye was not seeded for experiment 3.

Table 4.3. Analysis of variance for total seasonal dry matter production, sheep biomass utilization, residual dry matter biomass and weed biomass as affected by green manure species ([S] pea/oat and oat), and experiments (1, 2 and 3).

Source of Variation	Dry matter production	Sheep utilization	Dry matter residual	Weed biomass
	------------------------*P* values----------------------			
Species (S)	0.007*	0.06	0.05	0.22
Experiment (E)	0.69	0.22	0.14	0.09
S x E	< 0.001*	0.54	0.10	0.11

*Significant according to Fisher LSD test ($p < 0.05$).

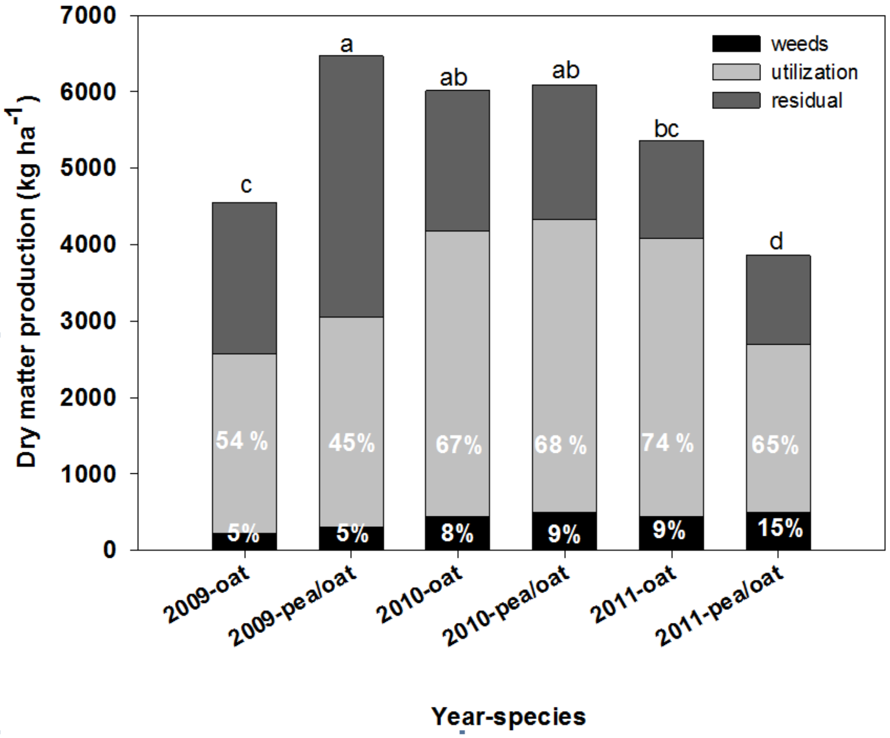

Figure 4.1. Total seasonal dry matter production, utilization by sheep grazing, post grazing residual biomass of green manures and weed biomass as influenced by experiment (1, 2 and 3) and green manure species (pea/oat and oat)(n=24). Percentage numbers in columns indicate the proportion of biomass consumed by sheep (termed utilization) and proportion of weed biomass (termed weeds). Columns with different letters are significantly different according to Fisher protected LSD ($p \leq 0.05$). Standard error for the effect of species x experiment interaction was 378, 5.6 and 2.7 for total dry matter production, utilization and weeds, respectively. LSD for the effect of species x experiment interaction was 853, 18.7 and 7.7 for total dry matter production, utilization and weeds respectively.

Table 4.4. Analysis of variance for all years of experiments 1, 2 and 3, as well as effect of green manure species (oat and pea/oat) and management on soil NO_3-N, P and K.

		Source	NO_3-N					P	K
Ex	Years	of Variation	0-30cm	30-60cm	60-90cm	90-120cm	Total	0-30cm	0-30cm
			---*P* values---						
1	Year 1	Species (S)	0.003*	0.37	0.35	0.10	0.03*	0.41	0.21
	(Green Manure)	Management (M)	0.002*	0.35	0.66	0.61	0.02*	0.35	0.28
		S x M	0.20	0.94	0.52	0.61	0.34	0.43	0.90
1	Year 2	S	0.16	0.28	0.18	0.16	0.16	0.23	0.27
	(Wheat)	M	0.23	0.82	1.00	0.11	0.66	0.34	0.18
		S x M	0.41	0.51	0.07	1.00	0.93	1.00	0.10
1	Year 3	S	0.07	0.23	0.07	0.34	0.14	0.29	0.79
	(Fall rye)	M	0.02*	0.23	1.00	0.77	0.11	0.35	0.28
		S x M	0.12	1.00	0.42	0.77	0.86	0.74	0.11
2	Year 1	S	0.06	0.02*	0.03*	0.17	0.02*	0.34	0.05*
	(Green Manure)	M	0.08	0.07	0.14	0.23	0.02*	0.47	0.45
		S x M	0.22	0.73	0.67	0.73	0.28	0.24	0.06
2	Year 2	S	0.18	0.17	0.19	0.43	0.16	0.72	0.72
	(Red root pigweed)	M	0.17	0.28	0.16	0.39	0.15	0.57	0.33
		S x M	0.37	0.52	0.61	0.77	0.41	0.57	0.24
2	Year 3	S	0.10	0.39	1.00	1.00	0.21	0.49	0.28
	(Fall rye)	M	0.34	0.17	1.00	0.25	0.10	0.17	0.18
		S x M	1.00	0.17	0.03*	1.00	0.34	0.04*	0.10
3	Year 1	S	0.01*	0.31	0.19	1.00	0.002*	1.00	0.42
	(Green manure)	M	0.05*	0.06	0.19	1.00	0.03*	0.27	0.64
		S x M	0.72	0.78	0.19	0.50	0.98	1.00	0.37
3	Year 2 (Wheat)	S	0.70	0.18	1.00	0.32	0.84	1.00	0.74
		M	0.13	0.11	0.11	0.44	0.91	0.10	0.36
		S x M	0.58	0.39	0.39	0.80	0.74	0.54	0.44

*Significant according to Fisher LSD test ($p < 0.05$).

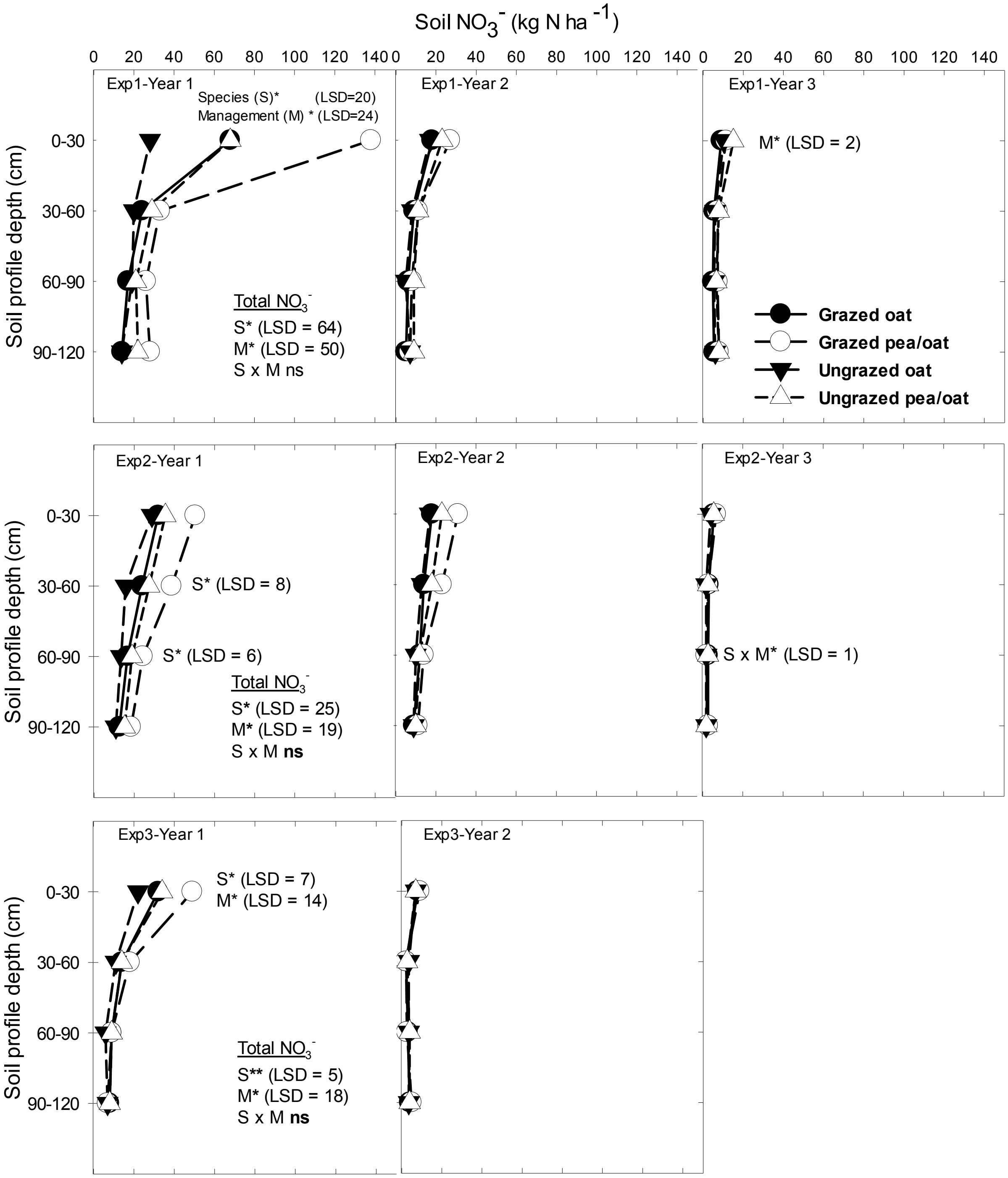

Figure 4.2. Soil NO_3-N as affected by green manure species ([S] pea/oat and oat) and green manure management ([M] grazing and incorporation) at depths of 0-30, 30-60, 60-90 and 90-120 cm over three years for experiments 1, 2 and 3. Please refer to Table 4 for analysis of variance of soil NO_3-N as affected by species and management. *Significant at $p \leq 0.05$. ** Significant at $p \leq 0.01$. ns not significant.

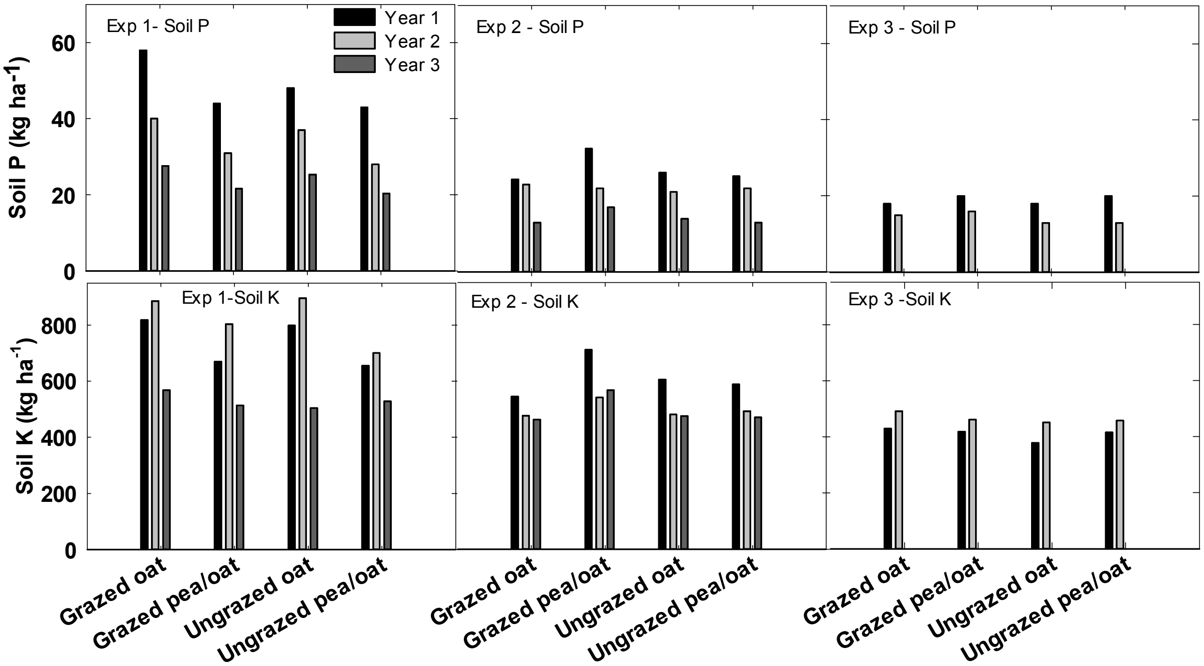

Figure 4.3. Soil phosphorus (P) and potassium (K) as affected by green manure species ([S] pea/oat and oat) and management ([M] grazing and incorporation) at depth of 0-30 cm over three years for the experiments 1, 2 and 3. There were no significant treatment or interaction effects for all years and experiments. Please refer to table 4 for analysis of variance for soil P and K as affected by species and management.

Table 4.5. Wheat above-ground biomass production at soft dough stage, nitrogen uptake, grain yield and grain protein concentration as affected by green manure species (pea/oat and oat) and management (grazing and incorporation) for the experiments 1, 2 and 3.

	Wheat soft dough biomass			Wheat soft dough N			Wheat yield			Wheat grain protein concentration		
Main effects	2009	2010[a]	2011	2009	2010[b]	2011	2009	2010	2011	2009	2010	2011
Green manure species	--kg ha^{-1}--									-------------g kg^{-1}---------		
Pea/oat	11536	3471	8126	138a	64a	73	3603a	-[c]	2903	159a	-	141
Oat	9726	2645	8228	80b	44b	58	3042b	-	2699	136b	-	130
Green manure management												
Grazing	11238a [d]	3103	8598	114	54	80a	3430	-	2903	150	-	139
Incorporation	10026b	3013	7756	106	54	51b	3217	-	2699	146	-	132
Source of Variation												
Species (S)	0.05	0.11	0.86	<.001	0.03	0.11	0.03	-	0.25	0.02	-	0.19
Management (M)	0.04	0.77	0.14	0.51	0.95	<.001	0.08	-	0.11	0.44	-	0.16
S x M	0.12	0.42	0.67	0.76	0.24	0.16	0.08	-	0.62	0.48	-	0.51

[a] Redroot pigweed biomass.

[b] Redroot pigweed N uptake.

[c] Wheat failed to grow in 2011.

d Within columns of same main effect, numbers followed by the same letters are not significantly different according to Fisher LSD test ($p < 0.05$).

Table 4.6. Fall rye soft dough stage biomass production, nitrogen uptake, grain yield and grain protein concentration as affected by green manure species (pea/oat and oat) and management (grazing and incorporation) for the experiments 1 and 2.

	Fall rye soft dough biomass		Fall rye soft dough N		Fall rye yield		Grain protein concentration	
Main effects	2009	2010	2009	2010	2009	2010	2009	2010
Green manures	--kg ha^{-1}-------------------------------------						---------------g kg^{-1}---------	
Pea/oat	7958a[a]	6500	54a	25	1978	3316	95	76
Oat	6187b	6512	32b	21	1686	3128	86	75
Management								
Grazing	7292	6378	43	22	1600	3271	91	76
Incorporation	6854	6633	42	24	2064	3173	91	76
Source of Variation								
Species (S)	0.02	0.99	0.005	0.52	0.42	0.41	0.15	0.77
Management (M)	0.49	0.41	0.85	0.33	0.19	0.48	0.97	0.87
S x M	0.44	0.76	0.52	0.94	0.92	0.89	0.11	0.60

a Within columns of same main effect, numbers followed by the same letters are not significantly different according to Fisher LSD test ($p < 0.05$).

Table 4.7. Wheat + fall rye soft dough biomass N uptake, residual soil NO_3-N after fall rye harvest and the total of these two parameters as affected by green manure species (pea/oat and oat), management (grazing and incorporation) and experiments (1 and 2). Total plant available N supply was calculated as the sum of plant N uptake (wheat and rye years combined) plus residual soil N after rye harvest.

Main effects	Wheat + fall rye	Residual	Total plant
Species (S)	--------------------kg ha^{-1}-----------------		
Pea/oat	144a[a]	17	161a
Oat	90b	19	109b
Management (M)			
Grazed	122	19	142a
Ungrazed	111	17	128b
Experiments (E)			
1	156a	24a	179a
2	78b	13b	91b
S x E			
Pea/oat E1	197a	21	218a
Pea/oat E2	90b	13	104c
Oat E1	114b	26	140b
Oat E2	66c	12	78c
Source of Variation			
Species (S)	<0.001	0.33	0.002
Management (M)	0.01	0.05	0.03
Experiment (E)	0.003	0.007	<0.001
S x M	0.58	0.40	0.65
S x E	0.005	0.08	0.03
M x E	0.05	0.80	0.05
S x M x E	0.17	0.67	0.12

a Within columns of same main effect, numbers followed by the same letters are not significantly different according to Fisher LSD test ($p < 0.05$).

CHAPTER 5

FORAGE POTENTIAL OF SIX LEGUMINOUS GREEN MANURES AND EFFECT OF GRAZING ON FOLLOWING GRAIN CROPS

5.1 Abstract

There is a need to design intensive cropping systems that can reap multiple benefits from annual forages: animal feed, soil fertility and weed control. Considering pea/oat as a standard green manure, this study investigated the productivity, weed competitiveness, utilization and N benefit from grazed and ungrazed green manures to wheat (*Triticum aestivum* cv. Waskada) and fall rye (*Secale cereale* cv. Hazlet). A three-year experiment was carried out in Carman, Manitoba, Canada in 2009 and repeated in 2010 and 2011. Green manures were grazed by three ewes and two lambs for 24 h (1667 sheep d/ha). Averaged over experiments pea/oat mix (*Pisum sativum* cv. 40-10/ *Avena sativa* cv. legget), hairy vetch (*Vicia villosa* L.) and sweet clover (*Melilotus officinalis* cv. Norgold) above ground dry matter (DM) production were 5036, 5032 and 4064 kg ha^{-1}, respectively. Lentil (*Lens culinaris* cv. Indianhead), a mixture of seven species and soybean (*Glycine max* cv. Prudence) produced the least amount of DM over three years; 3589, 3551, 3174 kg ha^{-1}, respectively. Pea/oat and hairy vetch were the most weed competitive species and averaged over three years contained less than 15% weed DM. Utilization of green manures by grazing animals was similar among species and ranged from 28% to 86% but the most common range was between 60% and 80%. Averaged over three years, wheat grown in grazed plots took up 107 kg N ha^{-1} versus wheat in

ungrazed plots taking up 98 kg N ha^{-1}. A significant species x management interaction effect for total (wheat + fall rye) N uptake in 2009 indicated that increasing the proportion of legumes in the green manure, increased N benefit from grazing. Fall rye productivity was not affected by grazing. In conclusion, pea/oat and hairy vetch were the two green manure species that resulted in the best overall systems performance, i.e. high levels of DM, good weed competition, were readily utilized by sheep and provided N benefit to following wheat and fall rye crops.

5.2 Introduction

Including forages in grain rotations improves productivity, economic returns, soil health and ecosystem functioning (Entz et al., 2002). Despite well-known advantages regarding forage-crop rotations, only 5 to 15% of arable land in the Northern Great Plains is rotated with forages (Entz et al., 1995). Profitability and economic stability of cropping systems improve when 2 or 3 years of forages are included in crop rotations (Davis et al., 2012). However, in intensive crop production systems, farmers are interested in shorter duration annual forages. Returns from annual forages can be optimized when multiple benefits are drawn from them: soil fertility, weed competition and animal live weight gains from grazing forage DM (Sims and Slinkard, 1991).

Historically, annual forages have received limited attention in the Northern Great Plains as a result of high establishment cost and emphasis on grain monocultures encouraging grain-finished livestock (McCartney et al. 2008). Recently, increasing cost of grain feeding and environmental concerns regarding confined animal operations have renewed the interest in the use of annual forages in livestock production systems. Marketing opportunities for pasture- or grass-fed meat products are increasing but there is a knowledge gap for potential annual forage species to be used in such systems. Annual forages are generally cut as hay in conventional systems, and, used as green manures for soil fertility in organic systems (Entz et al., 2001). Information is limited on potential green manure species and mixtures to be used for soil N building in organic systems.

For many crops, legume biomass needs to provide at least 110 kg N ha^{-1} for yields in legume-based systems to be similar to synthetic fertilizer based systems (Tonitto et al., 2006). Assuming that on average 20-25 kg of shoot N is fixed for every 1000 kg ha^{-1} of above ground dry matter of legume (Peoples et al., 2001), at least 5000-6000 kg ha^{-1} of legume biomass is required to meet the cash crop N requirement in the following year. Annual legume forages can often produce more than 5000 kg ha^{-1} (McCartney and Fraser, 2010), however, mineralization of organic N in legume biomass may not be in synchrony with the subsequent cash crop N uptake (Crews and Peoples, 2005). A number of factors can affect the N contribution from annual forages; the forage type, dry matter biomass production, time and type of incorporation, and residue placement (Mohr et al., 1998a, 1998b; Shrestha et al., 1999; Vaisman et al., 2011). Closer contact of plant material with soil microorganisms (i.e. incorporation) results in faster N mineralization than when it is left on the soil surface (i.e. rolled mulch) (Vaisman et al., 2011). Similarly, even faster N mineralization can be achieved when plant material is digested in the rumen of, for instance, cattle (*Bos taurus*) or sheep (*Ovis aries*) (Russelle, 1992). Hence, grazing of green manures may improve the N availability to following cash crops.

When used as a soil fertility-building tool before cash crops, a green manure year incurs cash crop opportunity loss. Alternatively, when harvested from the land as animal feed, nutrients are removed from the system (Entz et al., 2002). Grazing of green manures by ruminants has been suggested as a way to improve economic and soil fertility building value of green manures (Gardner and Faulkner, 1991; Thiessen Martens and Entz, 2011). Such integrated crop-livestock systems minimize external inputs and improve nutrient cycling (Davis et al., 2012; Wilkins, 2008).

An additional benefit of annual green manures or forages is the potential to shift weed community composition and reduce the need to use herbicides (Schoofs and Entz, 2000). Legumes and cereal-legume mixture green manures are preferred in organic systems because of legumes' ability to fix atmospheric nitrogen. However, legumes are weak competitors with weeds because of a long lag time between the establishment and the formation of a competitive ground cover (Sims and Slinkard 1991). Reduced herbicide use in legume stands increases the proportion of weed biomass in total forage yield but nutritional quality of weedy forages may be similar to solid stands of forages (Moyer and Hironaka, 1993). Nevertheless, in organic systems legumes are expected to have proportionally higher biomass when grown in mixtures with non-legumes because of legumes' advantage to grow better in low N soils. Weed competitiveness of annual legumes in crop-livestock systems needs to be investigated.

Recently there has been renewed interest in grass/legume intercropping. A number of researchers in northern climates have evaluated and recommended pea/oat mixture as a potential forage mix that can be adopted in low input systems (Carr et al., 2004; Begna et al., 2011). Cicek et al. (2014b) showed that soil nitrate content was higher after grazed oat (*Avena sativa*) and pea/oat (*Pisum sativum* / *Avena sativa*) plots than ungrazed ones. Although the magnitude of increase in soil nitrate content after grazing was similar for both crops, grazed pea/oat contributed more N to the system than grazed oat. It may be possible to increase the magnitude of N availability compared to pea/oat mixture if pure legume stands are grazed, because the nitrogen content of urine increases with increased N concentration of the forage (Kyvsgaard et al., 2000).

Although forage potential of many annual forage species has been evaluated, very few studies used actual grazing as a management effect (McCartney et al., 2008). Most research has focussed on hay, silage or swath grazing potential of annual forages (McCartney et al., 2004; Tanaka et al., 2005). In integrated crop-livestock systems annual forages are expected to provide both animal feed and enhanced soil fertility. There is a need to establish the effect of grazing of annual forages on soil fertility and subsequent crop productivity. In conventional systems, nutritional composition and dry matter productivity of several annual forages have been investigated (McCartney et al., 2008; 2009 and 2010). However, there is little information regarding weed competitiveness and palatability of potential green manure species. Particularly in organic systems, where soil management history may produce different soil fertility (van Diepeningen et al., 2006) and weed pressure (Ryan et al., 2010) than conventional systems, such information is critical. Therefore, selection criteria for annual forages in organic systems should include: i) sufficient dry matter biomass production for livestock, ii) nutritional quality and palatability of forage for grazing livestock, iii) weed competitiveness, and, iv) nitrogen contribution to following cash crops.

The present work is an extension of the earlier study (Cicek et al., 2014b) where the grazing effect on the N availability in grass/legume (pea/oat) versus grass (oat) green manure systems was described. This study compares pea/oat green manure to four legume species and one multispecies mixture. Specifically, the objectives of the present experiment were to investigate: i) productivity, weed competitiveness and livestock utilization of six green manures, ii) compare the productivity, weed competitiveness, utilization and N benefit of various legume species against pea/oat standard green manure, and iii) wheat and fall rye productivity and N uptake responses to two green manure management factors; grazing versus incorporation. We hypothesised that more N will be available to wheat and fall rye upon grazing of pure legumes compared to grazing pea/oat. The outcome of this study will assist our quest to identify annual green manure forages that fit into organic systems of temperate regions.

5.3 Materials and Methods

Site description and experimental design

All three experiments were conducted at the University of Manitoba Ian N. Morrison Research Farm in Carman, Manitoba (49°29′48″ N, 98°2′ 26″ W, 267 m above sea level). The region is characterized by an extreme continental climate with very cold winters and warm summers. Frost-free period for crop production is 115-125 days, and occurs primarily between May and September (MASC, 2013). Long-term average temperatures, precipitation, as well as 2009-2012 growing season monthly temperatures and precipitation are provided in Table 5.1. Soils at Carman are well drained Orthic Black Chernozems with a fine sandy loam texture (Mills and Haluschak, 1993). Two meters deep clay substrate underlies the soils, which are lacustrine and deltaic sediments with slope of less than 1%, pH of 6.2, and an organic matter content of 25 g kg^{-1}. Soil background nutrient samples were collected at 0-30cm for the experiments 2 and 3. Soil NO_3-N, P (Olsen) and K levels in the experiment 2 were 11, 20 and 569 kg ha^{-1}, and, in the experiment 3 they were 13, 17 and 477 kg ha^{-1}, respectively. No background soil samples were collected for the experiment 1. Oat was the preceding crop for all experiments. Previous investigations of integrated crop-livestock systems have been exclusively conducted under conventional management with fertilizer inputs. The present study was conducted under long term organic management (since 2004) with no external inputs.

The experimental design was a split-plot design, with four blocks. The whole-plot treatment was green manure species, and the sub-plot treatment was green manure management. Six green manure species (see Table 5.2) and two green manure management systems (grazed and incorporated) were included. Sweet clover and mixture were not present in experiment 1 but added to experiments 2 and 3. Therefore, combined wheat and fall rye responses were determined only for three annual legume species (hairy vetch, lentil and soybean) and pea/oat mix. The grazing green manures experiment started in 2009 (Experiment 1) and was repeated in 2010 (Experiment 2) and 2011 (Experiment 3) on neighboring sites within the experimental station. In the first year of the experiment, green manures were seeded in the spring, and grazed or incorporated in mid- to late-summer. In the second year, a spring wheat crop was seeded in May on the grazed and incorporated green manure plots. In the third year, a fall rye crop was grown.

Experiment 1 and the experiment 2 included all three phases of the experiment, but experiment 3 included only two phases (green manure year and spring wheat year).

Spring wheat establishment in experiment 2 failed as a result of higher than normal precipitation in fall 2010 and spring 2011. Therefore, wheat biomass samples were collected at stem elongation stage for experiment 2. Up to 70% of the wheat biomass samples in 2010 consisted of weeds (data not shown).

Green manure species and management

Green manure species, cultivar name, seeding rate and seeding date are provided in Table 5.2. Sweet clover was seeded in the autumn prior to the growing season by hand broadcast. All the other green manures were seeded using a JT-A10 air drill seeder (R-Tech Industries Ltd. Homewood, MB) with a row spacing of 20 cm. Timing for grazing green manures depended on the amount of biomass production and generally coincided with full bloom stage for legumes and milking stage for oats. Legumes were all inoculated with the appropriate rhizobium species. Cell-Tech liquid inoculator (Novozymes, Franklinton, NC) was used for soybean. For pea, lentil and hairy vetch we used NitraStic-C peat based inoculant (Novozymes, Franklinton, NC). Both inoculants were applied at the manufacturer’s recommended application rate of 75 mL of inoculant per 27 kg of seed. Sweet clover was inoculated with powder inoculant Nitragin Gold (Novozymes, Franklinton, NC).

Please refer to Chapter 4, Materials and Methods section for more detailed description of livestock management. Stocking density was determined based on available green manure DM. Stocking density ranged from 2 to 3 ewes (South African Dorper) and 2 to 5 lambs for 24 h (1111 to 1667 sheep d/ha). Sub-plots were 2 m wide and 9 m long and were surrounded by metal fences for precision and protection. Sheep were put into conditioning plots containing each green manure crop for 24h before they were put into actual experimental plots. As such, sheep started to consume the green manure species being tested a day before they were put into actual plots. Water buckets and shade tents were positioned in opposite ends of the plots to prevent uneven nutrient distribution. A blade-roller was used to terminate the ungrazed side of the green manure plots as soon as the sheep started terminating the grazed side. Blade roller equipment is able to kill green manures by crimping action (Vaisman et al. 2011). Both plots were tandem-disked at the same time upon the completion of grazing.

Upon green manure grazing in the first year, spring wheat (*Triticum aestivum* cv. Waskada) and was seeded in the second year as a first test crop. Fall rye (*Secale cereale* cv. Hazlet) was seeded after wheat harvest in the autumn and as a second test crop. Spring wheat and fall rye were also seeded using a JT-A10 air drill seeder with a seeding rate of 125 kg ha^{-1} and 110 kg ha^{-1}, respectively.

Plant sampling

Green manure above-ground DM production in year 1 was determined by clipping 2 x 0.4 m^2 randomly chosen samples from each experimental unit before grazing. Utilization was calculated as the percentage of forage dry matter consumed by sheep. Percent forage utilization by grazing was determined by taking residual above-ground biomass (2 x 0.4 m^2) from grazed plots within 3 days after the end of the grazing period. This biomass was washed (to eliminate soil and faeces adhering to residual biomass) and dried for 48 h at 60 °C, then weighed for dry matter content. For experiment 1, post-grazing residual biomass was not washed before drying and weighing. For the experiments 2 and 3, when conditions were much wetter during grazing, soil had to be washed off of residual plant material in order to get accurate plant DM.

Weed DM was determined by hand-sorting green manures and by weighing weeds after drying for 48 h at 60 °C. Common weed species were Canada fleabane (*Conyza canadensis*), barnyard grass (*Echinochloa crus-galli*), lamb's quarters (*Chenopodium album*), redroot pigweed (*Amaranthus retroflexus*), yellow foxtail (*Setaria glauca*), green foxtail (*Setaria viridis*), shepherd's-purse (*Capsella bursa-pastoris*), wild buckwheat (*Polygonum convolvulus*), lady's thumb (*Polygonum persicaria*), Canada thistle (*Cirsium arvense*), quackgrass (*Elymus repens*), and dandelion (*Taraxacum officinale*).

Spring wheat and fall rye biomass samples were harvested at the soft dough stage from 2 x 0.4 m^2 areas in each experimental unit, dried for 48 h at 60 °C and weighed. Spring wheat and fall rye grain for yield estimation was collected from each plot using a Kincaid 8-XP (Kincaid Equipment Manufacturing, Haven, KS) plot harvester. Dry wheat and fall rye DM samples were ground with a Wiley Mill (No.1 Arthur H. Thomas Co., Philadelphia, PA). Wheat and fall rye grains were ground with a Cyclone Lab Sample Mill (UDY Corporation, Fort Collins, CO). All ground samples were subsampled and analyzed for N concentration by combustion analysis using a LECO FP-528 (LECO, St. Joseph, MI). Wheat and fall rye N uptake at soft dough were calculated as the product of above-ground DM production (kg ha^{-1}) and its N concentration.

Statistical analysis

Statistical Analysis System program (SAS Institute, 2001) PROC MIXED procedure was used for data analysis. We used ANOVA and considered treatment effects as fixed effects and replications as random effects for all measurements. Assumptions of ANOVA were tested by using the PROC UNIVARIATE procedure. All data were verified for normality of residuals and homogeneity of variance. Differences were considered significant at $p < 0.05$ and means were separated using a Fisher's protected LSD test.

5.4 Results and Discussion

Green manure DM production

Precipitation varied over three years and affected forage biomass production. When precipitation was at long-term average levels in 2009 (experiment 1), hairy vetch and pea/oat produced the greatest amount of DM (Tables 5.1 and 5.3). During extremely wet conditions in 2010 and 2011 (experiments 2 and 3), hairy vetch and pea/oat produced on average 25% less DM than in experiment 1. Although the growing season precipitation was well above the long-term average in 2010, soils were not saturated in the spring of that year. In 2011, however, soils were saturated in spring because of the carryover moisture from 2010. Given this contrasting situation (i.e. early or late season excess soil moisture) pea/oat, mixture and sweet clover performed better under late season excess soil moisture (2010) conditions, and the rest of the crops performed under early season excess moisture conditions. Averaged across the experiments hairy vetch, pea/oat and sweet clover produced the greatest forage DM; 5036, 5032 and 4064 kg ha^{-1}, respectively

(Table 5.3). In experiment 2, sweet clover and pea/oat produced the greatest DM, while in experiment 3 hairy vetch produced the greatest DM. Lentil, mixture, and soybean produced the least amount of DM over three years; 3589, 3551, 3174 kg ha^{-1} respectively (Table 5.3).

Studies conducted in North Dakota, Manitoba and Alaska reported dry matter above ground DM production of pea/oat similar to the present study (Carr et al. 2004; Vaisman et al., 2011; Begna et al., 2011). In conventional systems, grass-legume mixtures (i.e. pea/oat) are used as a way to increase crude protein value of the forage compared to cereal monocropping (McCartney et al., 2010). In low-input systems, legumes are intercropped with grasses to capture atmospheric N, as well as, improve DM production, weed competition and soil health (Hauggaard-Nielsen et al., 2001). The value of intercropping to increase biomass production was not evaluated in the present study. Earlier studies reported inconsistent results as to the advantage of intercropping to increase biomass production (Carr et al., 1998; 2004).

Hairy vetch is commonly used as a winter annual to provide ground cover from autumn to spring (Teasdale et al., 2004) and as mulch in no-till crop production systems (Mischler et al., 2010; Halde et al., 2012). Hairy vetch is a common green manure in organic systems because it is an effective nitrogen supplier (Parr et al., 2011). In the present experiment, hairy vetch was evaluated as a spring seeded annual forage. Literature on spring seeded hairy vetch managed without weed control is scarce (Halde et al., 2012). When seeded in spring and weeds were controlled, hairy vetch produced an average of 6485 kg ha^{-1} across different locations in Alberta and Saskatchewan (Fraser et al., 2004). Hairy vetch DM production in the present experiment was 6202 kg ha^{-1} in a normal year (experiment 1) but around 25% less in wet years (experiments 2 and 3).

Sweet clover is a biennial, high N_2 fixing crop which is re-gaining its popularity especially among organic farmers. It is generally underseeded to cereal crops and the biomass production occurs in the second year. When underseeded to wheat, sweet clover produced average of 10130 kg ha^{-1} in one Alberta study (Blackshaw et al., 2001a), but an earlier Alberta study reported sweet clover DM production in the range of 1120 to 5830 kg ha^{-1} (Moyer et al., 2007). Unlike other crops which were seeded in spring, sweet clover in the present study was seeded in autumn previous to the grazing season. Sweet clover produced 5813 kg ha^{-1} of DM in experiment 2 when early season precipitation was normal, and 2316 kg ha^{-1} in experiment 3 when soils were saturated.

Exploitation of different nutrient niches within the cropping system is made possible by interseeding crops with varying ecophysiological traits (Smith et al., 2010). Mixtures of multiple species including warm and cool season crops, grasses, legumes and broadleaves have become more popular as annual forages and green manures. The mixture in this study produced a disappointing 3869 kg ha^{-1} in experiment 2 and 3234 kg ha^{-1}in experiment 3. In North Dakota, researchers have been exploring various “cocktail mixes” for late season grazing since 2007 (Sedivec et al., 2012). Various mixtures of warm season grasses, legumes and brassicas produced 2120 to 4207 kg ha^{-1} of above ground dry matter when seeded in mid to late summer (Fraase, 2012). No previous information on multiple species productivity as practiced in the present experiment is available from the Northern Great Plains region.

In summary, hairy vetch produced comparable or more DM than pea/oat standard green manure in all three years. Hairy vetch versus pea/oat DM production was 6202 and 6157 kg ha^{-1} in experiment 1, 4260 and 5589 kg ha^{-1} in experiment 2, and, 4645 and 3352 kg ha^{-1} in experiment 3 (Table 5.3). Sweet clover produced comparable or less DM than pea/oat, while other green manures always produced less DM than pea/oat. Based on the amount of DM production, hairy vetch and pea/oat are the most reliable species for annual forage production. Mixture and sweet clover produced less than hairy vetch and pea/oat. Lentil and soybean produced the least amount of DM. In summary, ranking the DM production was as follows hairy vetch = pea/oat > sweet clover = mixture > soybean = lentil.

Green manure weed competition

Legumes are poor weed competitors, therefore, weed control in both conventional and organic legume production is a challenge (Fraser et al., 2004; Fernandez et al., 2012). Including companion crops with legumes reduces the competitive ability of weeds (Finn et al. 2013). Intercropped pea/oat provided excellent weed control in this study. Averaged over three years, weed DM was less than 15% of the total pea/oat DM (Table 5.3). Hauggaard-Nielsen et al. (2001) showed that intercropped pea/barley was more effective at suppressing weeds than monocropped pea or barley. They determined that uptake of available inorganic N by barley limited the growth of weeds. The multispecies mixture used in the present study was not as effective at suppressing weeds as the pea/oat mix. In the mixture treatment 16 and 39 % of DM consisted of weeds in experiment 2 and 3, respectively (Table 5.3). Mixture was seeded in mid-June because it contained some warm season crops. Late seeding enabled warm season weeds such as barnyard grass (*Echinochloa crusgalli*), lamb's quarters (*Chenopodium album*), redroot pigweed (*Amaranthus retroflexus*) and yellow foxtail (*Setaria glauca*), reducing DM production and weed suppressing potential of the mixture. Inferior weed competitive ability of mixture in experiment 3 may be attributed to saturated soil conditions during seeding.

The second most weed competitive crop compared with pea/oat in this experiment was hairy vetch, which, averaged over three years, contained 15% weed DM (Table 5.3). Hairy vetch has been used as a solo crop, as well as, with other cereals to control weeds in organic (Leavitt et al., 2011; Halde et al., 2012) and conventional systems (Zotarelli et al., 2009). It is important to note that in many previous studies, hairy vetch was terminated with a roller crimper or herbicides, thereby adding new weed control beyond the vetch plant. However, hairy vetch living biomass can limit light penetration and prevent weed seed germination more effectively than mulched hairy vetch (Teasdale and Daughtry, 1993). In the present study we observed that the vine-like growth habit of hairy vetch provided thick biomass cover and prevented weeds from accessing sunlight.

Sweet clover was also a competitive crop when it produced a substantial amount of biomass as was the case in experiment 2. In experiment 3, however, sweet clover establishment was poor due to saturated soils, and weed DM accounted for 30% of total plant DM. In Alberta sweet clover biomass contained less than 12 % weed biomass when terminated in full bloom stage (Blackshaw et al., 2001b), showing the potential weed-smothering potential of this species.

Soybean is high quality forage for livestock (Sheaffer et al., 2001). Soybean and lentil forage DM contained 30 – 70% weeds, demonstrating that both crops failed to compete with weeds. While lentil is known to grow slowly at early vegetative stages (McDonald et al., 2007), the rate of growth of soybean is slow when temperatures are low (Badaruddin and Meyer, 2001) (i.e. spring temperatures in Manitoba), rendering both crops as poor weed competitors. When weeds were controlled with herbicides, forage and grain cultivars of soybean produced 5300 to 8400 kg ha^{-1} of DM (McCartney et al., 2010). Strategies such as using living mulch in organic soybean production may be an effective strategy to improve soybean biomass productivity. For instance, when Italian ryegrass was harvested and used as living mulch for no-till forage soybean, the need to use herbicide was eliminated (Kaneko et al., 2011).

Indianhead lentil was developed as a green manure crop for semi-arid environments (Biederbeck et al., 1993). In Manitoba, lentil grown as green manure produced 4820 kg ha^{-1} of DM when weeds were controlled (Bullied et al., 2002). Averaged over two years, lentil contained 68% weed DM, much greater than that in pea/oat (i.e. <15%). When grown as organic food grain, seeding dates (early versus late seeding) had no effect on weed DM in lentil (Fernandez et al., 2012). Baird et al. (2009) showed that weed suppressing ability and biomass of organic lentils increased asymptotically as the seeding rate increased (Baird et al., 2009). Seeding rate in the present study (205 seeds m^{-2}) was less than maximum suggested rate (375 seeds m^{-2}) by Baird et al. (2009). The lower seeding rate used in this study may have contributed to the low biomass production and consequent poor weed competitive ability of lentil.

None of the species tested in this present study provided weed control as consistent as that observed with pea/oat. Hairy vetch weed competition was similar to pea/oat in 2 of 3 years. Therefore, pea/oat was the most competitive forage tested in the present study.

Green manure utilization by sheep

Utilization for all forages ranged from 28 % to 86 % but the most common range was between 60% and 80% (Table 5.3). In experiment 1 the highest utilization rate was for lentil (82%) while sheep utilized other species at similar levels (28-45%). In experiment 2, utilization was similar for all species (68-81%) except for sweet clover (40%). Lower utilization of sweet clover in experiment 2 may be the result of high biomass production and the resulting woody stem of the sweet clover. In experiment 3, hairy vetch, pea/oat and mixture utilization rates were lower than other species. Generally, lower rates of utilization in experiment 1 can be attributed to the methodological error, where post-grazing residual biomass was not washed before drying and weighing. Averaged over the experiments, sheep appeared to consume more lentil (79%) and mixture (78%) biomass than other species. Averaged over the experiments utilization of other species ranged from 59 to 66%.

Although there is little information on palatability of annual forages, high utilization values observed in this study suggest that legumes and mixtures show promise as annual forages. In Minnesota soybean and cowpea were the most palatable forages compared to kochia (*Bassia scoparia*), rape (*Brassica* napus), amaranth (*Amaranthus caudatus)*, sudangrass (*Sorghum drummondii)*, turnip (*Brassica rapa*) and pearl millet (*Pennisetum glaucum*), where sheep utilized 82% of soybeans (Sheaffer et al., 1992).

Even though lentil and soybean forage biomass contained a high proportion of weed biomass, utilization by sheep was not decreased relative to less weedy forages (Table 5.3). Palatability and nutritional properties of some annual and perennial weeds have been shown to be comparable to common forage species (Marten and Anderson, 1975; Marten et al., 1987). In the present study some visual observations were made for the palatability of weed species. Sheep completely rejected Canada fleabane (*Conyza canadensis*) but consumed other weed species present; barnyard grass (*Echinochloa crus-galli*), lamb's quarters (*Chenopodium album*), redroot pigweed (*Amaranthus retroflexus*), yellow foxtail (*Setaria glauca*), green foxtail (*Setaria viridis*), shepherd's-purse (*Capsella bursa-pastoris*), wild buckwheat (*Polygonum convolvulus*), lady's thumb (*Polygonum persicaria*), Canada thistle (*Cirsium arvense*), quackgrass (*Elymus repens*), and dandelion (*Taraxacum officinale*). These observations indicate that grazing may be used to control weeds in organic systems. In the present study grazing was used during the green manure phase of an organic rotation. Grazing maybe used at other stages of organic rotations including, before seeding and after harvest (i.e. stubble grazing) of cash crops to control weeds (Lenssen et al., 2013)

Wheat and fall rye N uptake and productivity

Wheat and fall rye productivity, N uptake, yield and grain N concentration varied over three years responding to precipitation patterns (Table 5.1 and 5.4). Wheat productivity in experiment 1 was greater than experiment 2 and 3 because of floods in spring 2011 and drought conditions in summer 2012 inhibited the growth of wheat for experiment 2 and 3, respectively. Wheat grain yields in experiment 1 ranged from 3320 to 3603 kg ha^{-1}, which were comparable to regional conventional spring wheat yield averages (3500 kg ha^{-1}). As a result of floods in 2011 (experiment 2), wheat failed to establish and compete with weeds, therefore no yield data was collected. In experiment 3, as a result of dry conditions, wheat yields ranged from 2329 to 2903 kg ha^{-1}.

The pressing question in organic systems is how much of an increase in N availability is achieved upon grazing of legumes in comparison to soil incorporation. Cicek et al. (2014b) showed that soil NO_3-N at 0–30 cm was on average 25 % higher in grazed oat and pea/oat plots than ungrazed plots. However, higher NO_3-N availability in grazed plots did not always translate into higher wheat or fall rye N uptake in the following years. In the present study, when combined across experiments, there was a clear indication that grazing increased N availability to a following wheat crop (Table 5.4 and 5.5). The grazing effect was significant for wheat DM production, N uptake and grain N, but not significant for yield across experiments (Table 5.4). Averaged over three years, wheat grown in grazed plots took up 107 kg N ha^{-1} versus wheat in ungrazed plots taking up 98 kg N ha^{-1} (Table 5.5). Wheat N uptake in grazed plots in experiments 2 and 3 was 108 and 73 kg N ha^{-1} versus wheat in ungrazed plots 94 and 60 kg N ha^{-1} respectively. In experiment 1 there were no differences between grazed and ungrazed plots in terms of wheat N uptake; 134 vs. 138 kg N ha^{-1}. There are no studies comparing grazing of green manures to soil incorporation of green manures, which is a common management practice. Nitrogen availability from incorporated legumes maybe slower than synthetic fertilizers because most of the N in legume biomass is retained in organic form (Janzen et al., 1990). On the other hand, Bosshard et al. (2009) revealed that N availability from urine was comparable to N availability from a synthetic fertilizer; 41% versus 50% recovery by crops respectively.

Nutritional and non-nutritional benefits of legumes to following crops have been broadly discussed in the literature (Peoples et al., 1995; Lafond and Pageau, 2007). Legume biomass management to optimize the N benefit from legumes to following cash crops has also been investigated (Mohr et al., 1998a; Shrestha et al., 1999; Vaisman et al., 2011). Less attention has been paid to grazing of legumes and the nutrient availability to following crops in annual intensive systems. Researchers across the USA have shown improvement of crop productivity following swath grazing in North Dakota (Tanaka et al., 2005), winter cover crop grazing in Illionis (Maughan et al., 2009) and summer cover crop grazing under conventional tillage in Georgia (Franzluebbers and Studemann, 2007). Thus, the present study confirms the importance of grazing to increase N availability and productivity.

A major objective of this paper was to investigate whether more N was available upon grazing of legumes compared to pea/oat. Cicek et al. (2014b) showed that grazing a legume containing green manure (i.e. pea/oat) released more N than grazing of grass (i.e. oat). A significant species x management interaction effect (P = 0.076) for total (wheat + fall rye) N uptake in experiment 1 showed that while grazing hairy vetch and pea/oat biomass improved N availability, lentil and soybean did not (Table 5.4 and Figure 5.1). While total N uptake in grazed hairy vetch and pea/oat plots were more than in ungrazed hairy vetch and pea/oat plots, total N uptake was similar in grazed or ungrazed lentil and soybean plots. Both lentil and soybean above ground dry matter biomass contained more than 60% weed biomass, hence little legume biomass. Hairy vetch and pea/oat had at least 90% and 50% legume biomass. This suggests that higher proportion of legumes in green manures increases the N response of wheat to grazing. Although total N uptake was higher in grazed hairy vetch (246 kg N ha^{-1}) than grazed pea/oat (216 kg N ha^{-1}) for experiment 1, the difference was not statistically significant (Figure 5.1). There was no interaction effect for total N uptake in experiment 2 (Figure 5.1). Based on plant N uptake data, our hypothesis of increased availability of N upon grazing legumes versus pea/oat was rejected.

Similar observations were made for wheat N uptake when combined across three years. Wheat grown in grazed hairy vetch and pea/oat plots took up more N (126 and 120 kg N ha^{-1}) than wheat grown in ungrazed hairy vetch and pea/oat plots (104 and 98 kg N ha^{-1}). On the other hand wheat grown in grazed and ungrazed lentil and soybean plots took up similar amounts of N; 90 to 98 kg N ha^{-1}. If the benchmark set by Tonitto et al. (2006) was to be taken into consideration (i.e. need for legumes to supply at least 110 kg N ha^{-1}), then only grazed hairy vetch and pea/oat systems would meet the criteria for satisfactory N supply.

Fall rye productivity was not affected by management. There was a significant species effect for experiment 1 where fall rye grown in hairy vetch plots yielded more than fall rye grown in other plots. For the same experiment, grain protein was lowest for fall rye grown in lentil plots. Benefits of single year green manures to second year test crop were also observed by Bullied et al. (2002).

5.5 Conclusions

This study confirmed the green manure value of pea/oat and hairy vetch. Additionally, this study established the value of pea/oat and hairy vetch as annual forages for grazing. Pea/oat and hairy vetch produced high levels of biomass, competed with weeds, were readily utilized by sheep and provided N benefits to following wheat and fall rye crops. Lentil and soybean failed to compete with weeds, produced little biomass and did not provide N benefits to wheat and fall rye compared to pea/oat and hairy vetch.

Grazing pea/oat and hairy vetch improved wheat productivity and N uptake in comparison to soil incorporation of pea/oat and hairy vetch in one of three experiments. In other two experiments wheat productivity did not differ between treatments. Fall rye productivity was not affected by grazing. Importantly, there were no declines in wheat or fall rye productivity grown after grazing of green manures. Therefore, in addition to the single benefit of soil fertility, two benefits were reaped from green manures; potential livestock live weight gain and soil fertility.

We observed no wheat or fall rye yield advantage of grazing legumes over pea/oat. Future studies should investigate high biomass producing mixes with hairy vetch (i.e. barley/hairy vetch), which are becoming more popular among producers.

Tables and Figures

Table 5.1. Average monthly growing season air temperatures and precipitation for Carman, Manitoba, Canada from 2009 to 2012.

	Air temperature (°C)					Precipitation (mm)				
Month	2009	2010	2011	2012	30-year average[†]	2009	2010	2011	2012	30-year average[†]
April	2.9	8.7	4.5	6.2	4.2	23	35	44	19	42.5
May	8.5	11.6	10.4	12.1	12.5	74	159	72	61	52.7
June	15.4	16.3	16.7	17.7	16.9	127	63	59	86	72.8
July	16.9	19.6	20.3	21.9	19.4	62	48	38	28	69.1
August	17.1	18.7	19.3	19.0	18.2	53	138	12	47	65.5
September	17.3	11.8	14.0	12.5	12.2	18	107	65	3	49.0
October	3.6	8.3	8.2	4.2	5.5	28	57	8	85	34.0
Total (April-Oct.)						385	607	298	329	385

[†] from 1961 to 1990

Table 5.2. Green manure species common names, scientific names, cultivar name, seeding rate and date.

Common name	Scientific name	Cultivar	Seeding rate (kg ha^{-1})	Seeding date
Hairy vetch	*Vicia villosa*	VNS[†]	40	Mid-late May
Lentil	*Lens culinaris*	Indianhead	40	Mid-late May
Pea/oat mix	*Pisum sativum/ Avena sativa*	40-10/legget	100/50	Mid-late May
Soybean	*Glycine max*	Prudence	95	Mid June
Sweet clover	*Melilotus officinalis*	Norgold	10	September
Mixture				Mid June
Barley	*Hordeum vulgare*	Cowboy	28	
Field Pea	*Pisum sativum*	40-10	35	
Millet	*Pennisetum glaucum*	Red millet VNS	2.6	
Radish	*Raphanus sativus*	Groundhog	2.8	
Soybean	*Glycine max*	Prudence	22.5	
Turnip	*Brassica rapa*	Purple top VNS	0.6	
Sunflower	*Helianthus annuus*	Sanola	2.8	

[†] Variety not stated

Table 5.3. Green manure species biomass production, percent weed content and percent utilization by grazing animals for experiments (Exp) 1, 2 and 3.

	Biomass[†]			Weeds			Utilization		
Species	**Exp1**	**Exp2**	**Exp3**	**Exp1**[‡]	**Exp2**	**Exp3**	**Exp1**	**Exp2**	**Exp3**
	-----------------kg ha^{-1}-------			-----------------%---------------			-----------------%------------------		
Hairy vetch	6202a[§]	4260bc	4645a	<10	36b	0d	28b	81a	71bc
pea/oat	6157a	5589ab	3352bc	<10	9c	15cd	45b	68a	65c
Lentil	3442b	3536cd	3789ab	-	73a	64a	82a	71a	84a
Soybean	3540b	2606d	3376bc	30	70a	62a	40b	73a	85a
Mixture	-[¶]	3869cd	3234bc	-	16c	39b	-	76a	80ab
Sweet clover	-	5813a	2316c	-	n/a	30bc	-	40b	86a
P>F	0.0004	0.0015	0.0143	-	<.0001	<.0001	0.0008	0.0334	0.0055

† With weeds

‡ Visual ratings

§ Within columns of same main effect, numbers followed by the same letters are not significantly different according to Fisher LSD test ($p < 0.05$).

¶ Mixture and sweet clover were not seeded for experiment 1

Table 5.4. Analysis of variance for test crop (wheat and fall rye) above ground biomass, N uptake, grain yield, and grain N as affected by green manure species (pea/oat, hairy vetch, lentil and soybean), management (grazing and incorporation) and experiments (1 and 2).

	Test crop biomass		Test crop N uptake			Test crop yield		Test crop grain N	
Source of Variation	Wheat	Fall rye	Wheat	Fall rye	Wheat +Fall rye	Wheat	Fall rye	Wheat	Fall rye
	--*P* value--								
Green manure species	0.1666	0.0746	0.016	0.2026	0.0536	0.005	0.0004	0.0015	0.0623
Management (M)	0.0274	0.7064	0.009	0.3546	0.0241	0.430	0.3785	0.0004	0.8782
Experiment (E)	<.0001	0.1059	0.001	0.0102	0.0154	0.000	0.0015	0.0014	0.0442
S x M	0.0964	0.8817	0.002	0.2781	0.0767	0.614	0.7480	0.0782	0.8100
S x E	0.1624	0.1704	0.085	0.2097	0.1013	0.468	0.0144	0.0999	0.0487
M x E	0.3980	0.5596	0.380	0.2050	0.2702	0.324	0.5519	0.0430	0.7731
S x M x E	0.1959	0.9262	0.177	0.6819	0.0208	0.613	0.5710	0.4609	0.2198

Table 5.5. Wheat above-ground biomass production at soft dough stage, nitrogen uptake, grain yield and grain nitrogen content as affected by green manure species ([S] pea/oat, hairy vetch, lentil and soybean) and management ([M] grazing and incorporation) for experiments 1, 2 and 3.

	Wheat biomass			**Wheat N uptake**			**Wheat yield**			**Wheat grain N**		
Main effects	**Exp1**	**Exp2†**	**Exp3**	**Exp1**	**Exp2**	**Exp3**	**Exp1**	**Exp2¶**	**Exp3**	**Exp1**	**Exp2¶**	**Exp3**
Green manure species	kg ha^{-1}									g kg^{-1}		
Hairy vetch	11422	1872	8433a§	161	97	76	3335	-	2658a	176a	-	143a
Pea/oat	11538	2217	8126a	139	110	73	3603	-	2903a	160b	-	141ab
Lentil	11260	2045	6993b	122	91	50	3320	-	2329b	153b	-	124c
Soybean	11134	2250	8434a	120	106	63	3544	-	2751a	153b	-	141ab
Mixture	-‡	2211	8002a	-	109	68	-		2675a			129bc
Sweet clover	-‡	2383	7995ab	-	122	69	-		2705a			142ab
Management												
Grazed	11385	2224	8274a	134	111a	73a	3343	-	2720	2.83	-	141a
Ungrazed	11291	2102	7719b	138	100b	60b	3458	-	2620	2.79	-	131b
Analysis of Variance	*P* value											
Green manure species (S)	0.822	0.216	0.044	0.128	0.238	0.118	0.308	-	0.006	0.011	-	0.023
Management (M)	0.652	0.256	0.0004	0.674	0.035	0.004	0.907	-	0.126	0.210	-	<.0001
S x M	0.050	0.493	0.509	0.649	0.618	0.233	0.827	-	0.246	0.115	-	0.580

† Wheat biomass samples collected at stem elongation

‡ Mixture and sweet clover were not seeded in 2009

§ Within columns of same main effect, numbers followed by the same letters are not significantly different according to Fisher LSD test ($p < 0.05$)

¶ Wheat terminated after stem elongation samples in 2011, therefore no yield data available

Table 5.6. Fall rye above-ground biomass production at soft dough stage, nitrogen uptake, grain yield and grain nitrogen content as affected by green manure species ([S] pea/oat, hairy vetch, lentil and soybean) and management ([M] grazing and incorporation) for experiments 1 and 2.

	Fall rye biomass		Fall rye N uptake		Fall rye yield		Fall rye grain N (%)	
Main effects	Exp1	Exp2	Exp1	Exp2	Exp1	Exp2	Exp1	Exp2
Crop species	--------------------------------------kg ha^{-1}--						----------g kg^{-1}---------	
Hairy vetch	10004	7175	60	25	3010a‡	3340	97a	75
Pea/oat	7958	6500	54	25	1978b	3316	95a	76
Lentil	7312	6819	41	22	1394b	2943	86ab	77
Soybean	6700	6942	36	23	1604b	3120	83b	74
Mixture	-†	6305	-	21	-	3092	-	76
Sweet clover	-	6926	-	24	-	3237	-	74
Management								
Grazed	8175	6772	50	24	1909	3186	90	75
Ungrazed	7812	6781	46	23	2084	3163	90	75
Analysis of Variance	---*P* value---							
Green manure species (S)	0.1934	0.5467	0.1663	0.6819	0.0161	0.3209	0.0586	0.9245
Management (M)	0.6211	0.9754	0.1829	0.7644	0.4467	0.7967	0.9192	0.7650
S x M	0.8938	0.9832	0.2232	0.7969	0.6642	0.8596	0.4181	0.4812

† Not seeded

‡ Within columns of same main effect, numbers followed by the same letters are not significantly different according to Fisher LSD test ($p < 0.05$).

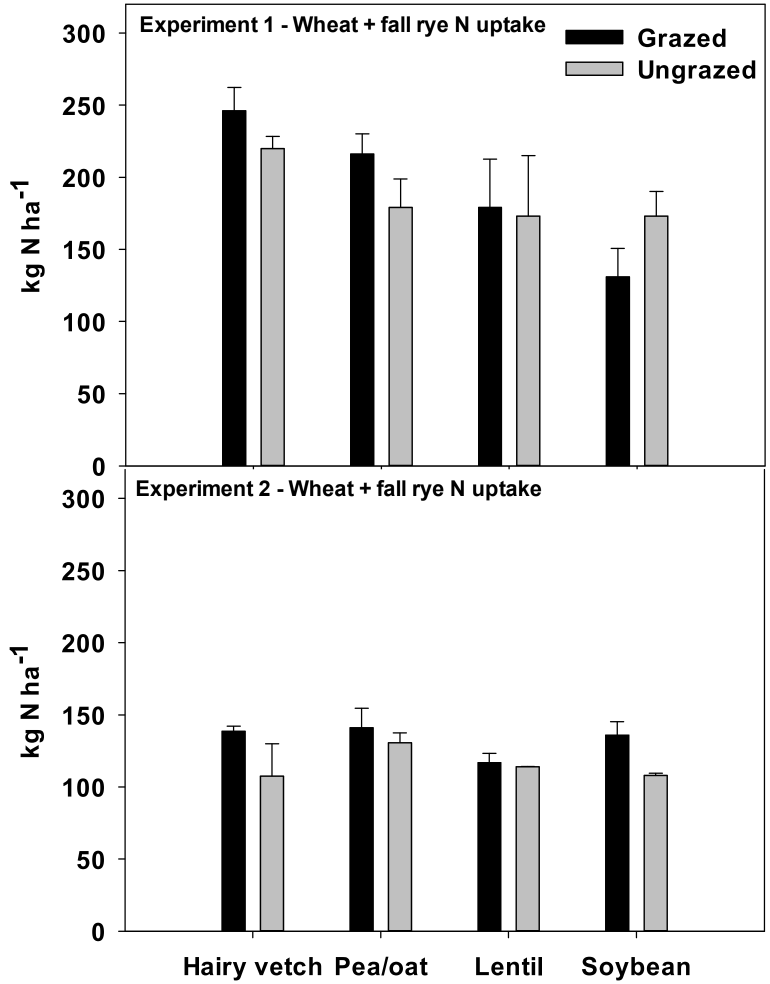

Figure 5.1. Total test crop (wheat + fall rye) nitrogen uptake for experiments 1 and 2 as affected by green manure species (pea/oat, hairy vetch, lentil and soybean) and management (grazing and incorporation).

CHAPTER 6

LATE-SEASON CATCH CROPS REDUCE NITRATE LEACHING RISK AFTER GRAZED GREEN MANURES BUT RELEASE MORE SLOWLY THAN WHEAT DEMAND

6.1 Abstract

Late season catch crops may be an effective tool to conserve highly available N after grazing of green manures. An experiment was established to investigate the productivity and N capturing abilities of barley (*Hordeum vulgare* cv. cowboy) and oilseed radish (*Raphanus sativus* L.) crops seeded after a grazed green manure. Green manure was a mix of forage pea (*Pisum savitum* cv. 40-10), soybean (*Gylicine max* cv. Prudence) and oat (*Avena sativa* cv. legget). The experiment was repeated twice in Carman, Manitoba in 2010 and 2011. Catch crops were seeded in late summer either no-till or after soil cultivation of the grazed plots. Wheat (*Triticum aestivum* cv. Waskada) was seeded in the second year as a test crop for both experiments. Catch crop productivity and N uptake were influenced by season (greater in the wetter year) and catch crop type (barley and radish produced 1994 and 1492 kg ha^{-1}, respectively) but not tillage system. The catch crops had their greatest overall effect on soil NO_3-N content in 2010 under conditions of high autumn precipitation when N leaching potential was more severe. Here, the catch crops significantly reduced NO_3-N at all depths. Under drier conditions in 2011, catch crops only reduced NO_3-N in the top 30 cm. There was average 57 and 12 kg ha^{-1} more soil NO_3-N in plots with no catch crops than plots where catch crops were grown in 2010

and 2011, respectively. Wheat N uptake at maturity was reduced around 25% when grown after catch crops. Similarly, wheat grain yield was 12 to 31% less after catch crops than no catch crops. This study showed that catch crops can be used to capture excess nutrients after grazing but N release from the selected catch crops in the following year was not in synchrony with the wheat N demand.

6.2 Introduction

Excessive nutrient application and losses occur in improperly managed conventional, organic and low-input cropping systems (Stopes et al., 2002). Catch crops are cover crops (i.e. non-commercial) that are grown with the purpose of capturing excess N and preventing leaching losses. Catch crops have been shown to be more effective in capturing excess nutrients than other management techniques such as reduced tillage and reduced N inputs (Thorup-Kristensen et al., 2003; Constantin et al., 2010). Catch crops can be included in the rotation in various ways depending on the cropping system. In conventional systems, catch crops are generally seeded after main crop harvest to capture excess nutrients (Herrera et al., 2010). In organic systems, catch crops are generally seeded after animal manure application to capture excess nutrients (Olesen et al., 2000) but rarely seeded after green manures. Because of greater availability of nutrients in grazed green manures systems (Cicek et al., 2014b), an important role of catch crops may be to capture excess nutrients after green manure grazing.

Nitrate (NO_3-N) is of particular importance in catch crop research. As a result of its negative charge, NO_3-N is highly mobile and can leach when N supply exceeds crop requirements. Nitrate leaching in agroecosystems is influenced by soil type, catch crop species, precipitation, temperature, N transformation rates (mineralization, immobilization, dentrification), N input type, drainage and tillage (Campbell et al., 2006; Constantin et al., 2010). Among these factors, catch crop species selection, management and N input type are among the most effective management tools for controlling NO_3-N leaching (Thorup-Kristensen et al., 2003; Constantin et al., 2010). For instance, catch crops were found to decrease N leaching 40-50% in conventional (Aronsson and Torstensson, 1998) and 30-38% in organic systems (Askegaard et al., 2005).

Excess precipitation is one of the main reasons for NO_3-N leaching (Thorup-Kristensen et al., 2003). Therefore, catch crop research has been concentrated in areas where annual precipitation is generally above the crop demand (i.e. north eastern USA, New Zealand and Northern Europe). Under such conditions, catch crops can limit NO_3-N loss by direct uptake of available NO_3-N and/or utilization of excess moisture, hence preventing downward water-bound NO_3-N movement (Thorup-Kristensen et al., 2003). Even under the relatively dry conditions in western Canada, Campbell et al. (1984) showed that NO_3-N leaching occurs when precipitation was above the long-term average. Nitrate leaching was more severe in rotations with fallow periods than intensive rotations with crops grown every year.

Grazing of green manures is a recently proposed management technique that has not been investigated in terms of NO_3-N leaching (Thiessen Martens and Entz, 2011). Since risk of NO_3-N leaching is aggravated under grazed systems compared to ungrazed systems (Ryden et al., 1984), there is an urgent need to investigate the risk of NO_3-N leaching in novel crop-livestock integrated systems that include grazed green manures.

Nitrogen loading under cattle (*Bos taurus*) and sheep (*Ovis aries*) urine patches can reach 1000 and 500 kg N ha^{-1} respectively (Haynes and Williams, 1993). Urea in urine patches quickly hydrolyses to NH_4^-, which can be quickly converted to NO_3-N (Di and Cameron, 2002). Unlike slowly mineralizing organic N in green manure residues, inorganic N in urine patches is more susceptible to volatilization, denitrification and leaching (Clough et al., 1998; Whitehead, 2000). Further, in grazed green manure systems, grazed plants are often annual species, hence, upon grazing no living plant cover is left behind. Under such circumstances risk of NO_3-N leaching may be greater than under perennial systems, where living plant cover can uptake at least some of the urine N deposited.

Nitrate is considered “lost” only when it leaches beyond the root zone (Thorup-Kristensen et al., 2003). Therefore, the “leaching” of NO_3-N down the soil profile is not equivalent to “leaching loss” of NO_3-N. Nitrate leaching losses under grasslands grazed by sheep with no synthetic N inputs is reported to be 6-7 kg N ha^{-1} y^{-1} in New Zealand (Ruz-Jerez et al., 1995). In the northeastern USA, Stout (2003) applied synthetic urine with N content of 442 to 1342 kg N ha^{-1} in a region where annual precipitation is around 930 mm. It was shown that regardless of the urine volume, approximately 25% of the applied urine was lost through leaching.

The proposed catch crop system represents a new frontier for the optimization of organic cropping systems. This new approach intensifies the green manure phase of organic rotations by adding grazing animals and catch crops. Grazing animals utilize green manures which otherwise is a lost revenue opportunity for the farmer, while catch crops increase biomass production on the same land base within one growing season. Long-term experiments have shown that adding organic matter and fertility through the use of late-season catch crops increases productivity of the agroecosystems (Constantin et al., 2010; Doltra and Olesen, 2013).

Species selection in catch crop studies is an important factor because N uptake capacity of catch crops is determined by speed of establishment, growth rate, rooting depth and cold tolerance (Munkholm and Hansen, 2012). The species selection not only affects N uptake, but also N availability to the subsequent cash crop from decomposing catch crop residue. Therefore, C:N ratio, lignin and N content of the catch crop species are important characteristics to be considered when selecting a catch crop species or mixtures (Thorup-Kristensen et al., 2003). One of the main challenges in legume-based systems is achieving the synchrony of N mineralization from green manures and cash crop demand (Crews and People, 2005; Tonitto et al., 2006). In general, N mineralization in crops with low C:N ratio (i.e. some brassicas and legumes) is faster than crops with high C:N ratio (i.e. grasses) (Ranells and Wagger, 1997; Constantin et al. 2011). Accordingly, the ideal catch crop species should readily capture available N after grazing and readily release N to the next crop, resulting in an effective N synchrony. Grasses such as barley (*Hordeum vulgare*) may be effective in capturing N because of its fast growth but release N slower because of its high C:N ratio. Brassicas such as oilseed radish (*Raphanus sativus*) are also known to have rapid N uptake (Thorup-Kristensen et al., 2003), but are thought to release N more quickly as a result of their lower C:N ratio.

Current attempts to reduce tillage in organic agriculture have focused on the green manure phase of the rotation (Peigné et al., 2007; Vaisman et al., 2011) and the system is referred to as organic rotational no-till (Halde et al., 2012). In organic agriculture, tillage is applied to control weeds, improve nutrient mineralization and prepare a seedbed. Grazing animals in integrated crop-livestock systems may provide these services by consuming the green manure biomass. For example, after grazing green manures, weeds and biomass left on the soil surface could be minimal (Hatfield et al., 2007c). Additionally, nutrients in faeces would reduce the need for tillage to mineralize nutrients. Hence, grazing animals may facilitate no-till seeding of catch crops after grazing of green manures.

An experiment was established to explore the soil NO_3-N uptake and release patterns of catch crops grown after a grazed green manure. The objectives of this study were to investigate: i) the biomass production and N uptake of two different catch crop species (barley and oilseed radish) seeded after a grazed green manure using no-till and tillage methods, ii) the effectiveness of catch crops in capturing N released in autumn by the grazed green manure, and, iii) the N availability to a following wheat crop. As a result of faster N mineralization under tillage (Varco et al., 1993), it was hypothesized that catch crops will produce more biomass and take up more N when grown in tilled plots as opposed to no-till seeded plots. It was also hypothesized that soil NO_3-N content would be lower in catch crop plots than no catch crop plots. Lastly, conservation of N in catch crop plots will increase the wheat productivity compared to no catch crop plots where N is not conserved in catch crop biomass.

6.3 Materials and methods

Site description and experimental design

Experiments were conducted at the University of Manitoba Ian N. Morrison Research Farm in Carman, Manitoba (49°29′48″ N, 98°2′ 26″ W, 267 m above sea level). The region is characterized by an extreme continental climate with very cold winters and warm summers. Frost-free period for crop production is 115-125 days, and occurs primarily between May and September (MASC, 2013). Long-term average temperatures, precipitation, as well as 2010-2012 growing season monthly temperatures and precipitation are provided in Table 6.1. Soils at Carman are well drained Orthic Black Chernozems with a fine sandy loam texture (Mills and Haluschak, 1993). Two meters deep clay substrate underlies the soils, which are lacustrine and deltaic sediments with slope of less than 1%, pH of 6.2, and an organic matter content of 25 g kg^{-1}. Soil background nutrient samples were collected at 0-30 cm for the experiments. Soil NO_3-N, P (Olsen) and K levels in the experiment 1 were 21, 24 and 544 kg ha^{-1}, and, in the experiment 2 they were 12, 18 and 712 kg ha^{-1}, respectively. Oat was the preceding crop for both experiments. Previous investigations of integrated crop-livestock systems have been exclusively conducted under conventional management with fertilizer inputs. The present study was conducted under long-term organic management (since 2004) with no external inputs.

The experimental design was a split-plot design, with four blocks. The whole-plot treatment was seeding management and the sub-plot treatments were catch crops. Two catch crop species and two catch crop seeding management systems were included. Control plots had no catch crops. The catch crop experiment started with an experiment in 2010 (Experiment 1) and was repeated in 2011 (Experiment 2) on a neighbouring site within the experimental station on the same soil type. In the first year of the experiments, green manures were seeded in the spring, and grazed in late summer. Catch crops were seeded as soon as the grazing was complete (Table 6.2). Catch crops were soil incorporated with a rototiller at the end of the season in early or mid October (Table 6.2). Spring wheat (*Triticum aestivum* cv. Waskada) was seeded in the second year as a first test crop for both experiments in the following spring (Table 6.2). Fall rye (*Secale cereale* cv. Hazlet) was seeded after wheat harvest in the autumn as a second test crop for experiment 1 only. Spring wheat and fall rye were seeded using a JT-A10 air drill seeder (R-Tech Industries, Homewood, Manitoba) with a row spacing of 20 cm and a seeding rate of 125 kg ha^{-1} and 110 kg ha^{-1}, respectively.

Green manure and catch crop species management

The green manure mixture of forage pea (*Pisum savitum* cv. 40-10), soybean (*Gylicine max* cv. Prudence) and oat (*Avena sativa* cv. legget) was seeded in the first week of June with the seeding rates that corresponds to 55, 85 and 140 seeds/m^2, respectively. All legumes were inoculated with the appropriate rhizobium species. Cell-Tech liquid inoculator (Novozymes, Franklinton, NC) was used for soybean and NitraStic-C peat based inoculant (Novozymes, Franklinton, NC) was used for pea. Both inoculants were applied at the manufacturer's recommended application rate of 75 mL of inoculant per 27 kg of seed.

Please refer to Chapter 4, Materials and Methods section for detailed description of livestock management. Timing for grazing green manures generally coincided with the full bloom stage for legumes and milking stage for oats. Stocking density ranged from 2 to 3 ewes (South African Dorper) and 2 to 5 lambs for 24 h (1111 to 1667 sheep d/ha).

Sub-plots were 2 m wide and 9 m long and were surrounded by metal fences for precision and protection. Sheep were put into conditioning plots containing green manure crops for 24 h before they were put into actual experimental plots. Preconditioning meant that sheep started to consume the green manure species being tested a day before they were put into actual plots. Water buckets and shade tents were positioned at opposite ends of the plots to prevent uneven distribution of feces and urine.

Catch crop species barley (*Hordeum vulgare* cv. cowboy) and oil seed radish (*Raphanus sativus* L.) were seeded either directly or after cultivation of the grazed plots at a seeding rate of 350 seeds/m^2. Catch crops were seeded using a no-till disc drill (Fabro Enterprises Ltd., Swift Current, SK) with a row spacing of 15 cm.

Plant sampling

Green manure aboveground biomass production in year 1 was determined by clipping 2 x 0.4 m^2 randomly chosen areas from each replicate both before and within 3 days of grazing. Forage utilization was calculated as the percentage of forage dry matter consumed by sheep by comparing biomass before and after grazing. In order to eliminate soil and faeces adhering to residual biomass, the post-grazing biomass samples were washed before drying for 48 h at 60 ^{o}C.

Catch crop biomass was collected from 2 x 0.4 m^2 randomly chosen areas in each plot, dried for 48 h at 60 ^{o}C and weighed for dry matter content. Growth rates of catch crops were calculated by dividing the total dry matter biomass production of a catch crop by the number of days from the seeding to termination of catch crops. Spring wheat and fall rye biomass samples were harvested at the soft dough stage from 2 x 0.4 m^2 randomly chosen areas in each experimental unit, dried for 48 h at 60 ^oC and weighed for dry matter content. Spring wheat and fall rye grain for yield estimation was collected from each plot using a Kincaid 8-XP (Kincaid Equipment Manufacturing, Haven, KS) plot harvester. Dry wheat and fall rye biomass samples were ground with a Wiley Mill (No.1 Arthur H. Thomas Co., Philadelphia, PA). Wheat and fall rye grains were ground with a Cyclone Lab Sample Mill (UDY Corporation, Fort Collins, CO). All ground samples were subsampled and analyzed for N concentration by combustion analysis using a LECO FP-528 (LECO, St. Joseph, MI). Wheat and fall rye N uptake at soft dough were calculated as the product of above-ground biomass production (kg ha^{-1}) and its N concentration.

Soil sampling

Background soil samples were taken immediately before grazing to the depth of 30 cm for both experiments. After seeding of catch crops there were five soil sampling dates for experiment 1, and three for experiment 2. Soil samples in experiment 1 were taken 30 days after seeding of catch crops (September 9, 2010) and on October 20, 2010, when catch crops were terminated. The first soil sampling for experiment 2 was in October 2011, at the time of catch crop termination. Since catch crops were seeded later in experiment 2 than experiment 1, only one soil sample (Oct. 20) was collected. Spring soil samples were taken on May 19, 2011 for experiment 1 and on April 25, 2012 for experiment 2, before wheat establishment. Soil was sampled again in autumn following wheat harvest (September 2011 and 2012). The final soil samples for experiment 1 were collected after fall rye harvest in September 2012.

Soil samples were collected using Dutch augers in 2010, and using a hydraulic soil coring rig (The Giddings Machine Co, Windsor, CO, USA) with a 4-cm diameter tip in 2011 and 2012. Soil samples were taken to 120 cm depth, at four depth increments; 0-30, 30-60, 60-90 and 90-120 cm. All soil samples were sent to Agvise commercial soil analysis laboratory for chemical analysis (AGVISE, Northwood, ND). Soil samples were analyzed for nitrate (NO_3-N) at all four depths using the cadmium reduction method, for plant available soil P at 0-30 cm depth using 0.5 M $NaHCO_3$ (P Olsen), and for soil K at 0-30 cm depth using 1 M $NH_4C_2H_3O_2$ extraction. Soil pH was determined with pH electrode in a 1:1 soil:water suspension. Soil organic matter was determined by loss of weight on ignition at 360^{o}C.

Statistical analysis

Statistical Analysis System program (SAS Institute, 2001) PROC MIXED procedure was used for data analysis. For the ANOVA, treatment effects were considered as fixed effects and replications as random effects for all measurements. Repeated measures were used to compare the effects of catch crop species and management on soil NO_3-N and wheat productivity over time. As required by analysis of residuals, logarithm transformation was used to achieve normality and homogeneity of variance for soil NO_3-N and wheat productivity data. Prior to analyzing each experiment separately, combined analysis was performed using catch crop species, seeding management and experiment as fixed effects. There were no three-way interactions (i.e. catch crop species x management x experiment). However, there were significant effects of species and experiment on almost all parameters (i.e. catch crop biomass, wheat N uptake), therefore, each experiment was presented separately. Assumptions of ANOVA were tested by using the PROC Univariate procedure. All data were verified for normality of residuals and homogeneity of variance. Differences were considered significant at $p < 0.05$ and means were separated using a Fisher's protected LSD test.

6.4 Results and Discussion

Environmental and field conditions

Precipitation varied greatly from 2010 to 2012, which affected catch crop and wheat production in both experiments. During the catch crop production phase for experiment 1 (in 2010), precipitation was almost twice the long term average (Table 6.1). Precipitation received during the catch crop phase of experiment 2 (August to October 2011) was 24 % lower than the long-term average (Table 6.1). As such, while the catch crop phase of experiment 1 was conducted under favorable conditions, deficit moisture conditions prevailed for experiment 2. Excess precipitation in autumn 2010 meant that the wheat production phase of experiment 1 and the green manure production phase of experiment 2 started with waterlogged soils.

Green manure dry matter biomass production was 5620 and 2780 kg ha^{-1} for experiment 1 and 2, respectively. Lower green manure biomass production in experiment 2 was attributed to excessively wet soils. Utilization of green manure by sheep was 66% and 44% for experiment 1 and 2, respectively. Lower utilization of green manures in experiment 2 may be the result of trampling or flattening of the already low amount of dry matter by sheep.

Catch crop productivity and N uptake

Barley and oilseed radish productivity in experiment 1 was 3438 and 2620 kg ha^{-1}, respectively compared to 551 and 364 kg ha^{-1}, respectively in experiment 2 (Table 6.3). Higher catch crop biomass production in experiment 1 than experiment 2 was attributed to the following. Catch crops were seeded earlier in experiment 1 than experiment 2 (August 9, 2010 vs. August 21, 2011; Table 6.2) and terminated later (October 21, 2010 vs. October 11, 2011; Table 6.2). Second, more moisture was available to catch crops in experiment 1 than experiment 2 (Table 6.1). Therefore it could be argued that catch crop production in experiment 1 was under ideal environmental conditions, while in experiment 2 the conditions were not favorable for late season plant growth. Results in the present study mirror those from other temperate environment catch crop studies. In Denmark, a series of catch crop experiments over 12 years tested various double-cropped or relay-cropped catch crop species and mixtures (Munkholm and Hansen, 2012). Relay-cropped perennial ryegrass (*Lolium perenne* L.) produced 1500 kg ha^{-1} of dry matter biomass, while fodder radish (*Raphanus sativus* L.) in the same study produced up to 1800 kg ha^{-1} of biomass when undersown to barley 2-3 weeks before barley harvest in early August. Fodder radish and oilseed radish are among the alternative common names for *Raphanus sativus*. In a long term study (17 years) in northern France, radish and Italian ryegrass catch crops produced 1470 and 2320 kg ha^{-1} of dry matter biomass, respectively (Constantin et al., 2010).

There is a limited amount of information on late season cover crops or catch crops in organic systems, particularly in the northern Great Plains of North America. Of the limited information available, most is focussed on relay-cropping (i.e. underseeding a cover crop into cash crop; Liebman et al., 2012 Blackshaw et al., 2010a). Whereas in the present study, catch crops were double-cropped. Thiessen Martens et al. (2001b) reported 746 and 634 kg ha^{-1} of biomass production for chickling vetch (*Lathyrus sativus* L.) and lentil (*Lens culinary* L.*),* respectively when double cropped after fall rye. Cicek et al. (2014a) reported that among the eight late season cover crops tested, only relay cropped red clover and double cropped forage pea produced acceptable amount of biomass from mid August to early October. Double cropped oilseed radish in their study produced up to 352 kg ha^{-1} when seeded after tillage, but produced only 67 kg ha^{-1} when no-till seeded.

Daily growth rates were significantly different between catch crop species in experiment 1 but not in experiment 2 (Table 6.3). In experiment 1, while barley grew at 47 kg ha^{-1} d^{-1}, oilseed radish grew at a rate of 36 kg ha^{-1} d^{-1}. In experiment 2 growth rates were much lower for barley (11 kg ha^{-1} d^{-1}) and oilseed radish (7 kg ha^{-1} d^{-1}). Two other studies also investigated growth rates of late season crops in Manitoba. In the first study, growth rates of four late season legumes ranged from 2 to 18 kg ha^{-1} d^{-1} (Thiessen Martens et al., 2001b). In the second study, growth rates of legumes under organic management ranged from 3 to 32 kg ha^{-1} d^{-1} (Cicek et al., 2014a). While growth rates of late season crops in the experiment 1 were much higher than two Manitoba studies, the rates were similar in experiment 2. Catch crops grew faster in experiment 1 than experiment 2 because of better growing conditions (i.e. early seeding, moisture and heat) in experiment 1. There was no seeding management effect on growth rates for both experiments, indicating that tillage did not affect plant growth differently between two plant species in this study.

There are two major differences between the present experiment and the two previous Manitoba studies (Thiessen Martens et al. 2001b, Cicek et al., 2014a). One difference is the crop type; non-legumes in the present study versus legumes in the previous Manitoba studies. The second difference is soil nutrient status. In the present study, catch crops were established after grazed legumes, where soil nutrient availability was expected to be high. In the two previous Manitoba studies were established after fall rye harvest where soil nutrient availability was expected to be low. Hence, faster growth rates of non-legumes in the present study may be explained by i) low post emergence growth rates of legume establishment compared to other crops (Liebman and Dyck, 1993; Biederbeck et al., 1993), or ii) higher N availability after grazing increasing the growth rates of catch crops (Berger et al., 2007).

It is also important to recognize that root biomass of catch crops was not investigated in the present study. In northern France, root biomass represented 15% of the total biomass of a forage radish catch crop (Constantin et al., 2010). The root:shoot ratio of annual cereals usually decrease toward maturity (Hoad et al., 2001). Since, in the present study, barley reached only booting stage (i.e. Zadoks 45-49), root biomass may have represented more than 50% of the total biomass (Hoad et al., 2001).

No differences in N uptake were observed between barley and oilseed radish. Barley and oilseed radish took up 55 and 58 kg N ha^{-1}, respectively in experiment 1, and 19 and 15 kg N ha^{-1}, respectively in experiment 2 (Table 6.3). Averaged over two years, Monkholm and Hansen (2012) also reported similar N uptake values for perennial ryegrass and fodder radish; 37 and 55 kg ha^{-1}, respectively. Averaged over 17 years, radish and Italian ryegrass catch crops took up 34 and 35 kg N ha^{-1} in northern France (Constantin et al., 2010).

Nitrogen concentration of oilseed radish (2.3 to 4.2%) was significantly higher than barley (1.6 to 3.5%) in both experiments. A similar observation was made in Denmark where oilseed radish (fodder radish) N concentration was highest among the three catch crops tested and N concentration ranged from 2.72 to 3.86% (Monkholm and Hansen, 2012). Similar to results with total biomass production, differences in N uptake and N concentration in the present study appeared to be related to differences in sowing date and weather conditions between experiments. Catch crop N uptake could be reduced 1 to 2 kg N ha^{-1} per day when seeded late (Vos and Van der Putten, 1997). In the present study, average N uptake was 0.8 kg ha^{-1} d^{-1} under the favourable growing conditions in experiment 1 compared with 0.3 kg ha^{-1} d^{-1} under dry conditions in experiment 2 (data not shown).

Averaged over two years barley produced more biomass than oilseed radish; 1994 vs. 1492 kg ha^{-1}. Despite the lower biomass amounts as compared to barley, oilseed radish took up similar amounts of N in the present study. Greater N uptake by oilseed radish may be attributed to its deeper root system (Thorup-Kristensen, 2001), faster nitrate uptake rates (Laine et al., 1993) and cold tolerance (Laine et al., 1994) in comparison to monocots (i.e. rye or Italian ryegrass).

There were no significant seeding management effects for catch crop biomass production, N uptake and N concentration in the present study (Table 6.3). Both crops performed similarly under both no-till and conventional seeding. These results are supported by studies from southern Brazil and Georgia USA where no-till seeded crops performed similarly to conventional tillage when grazing was the preceding management strategy (Franzluebbers and Studemann, 2007; Carvalho et al., 2010). The authors concluded that rumen processing of the green manures improved N availability to no-tilled crops. A similar conclusion can be made for the present study. Excellent growth of catch crops in the no-till system can be explained by the improved N availability after grazing. Slow N mineralization from green manures is one of the greatest challenges that organic no-till systems face (Vaisman et al., 2011). Grazing of green manures improves the N availability from green manures and may make organic no-till achievable. More research is needed to investigate strategic grazing of green manures to reduce tillage in organic systems.

Soil nitrate and N leaching potential

Soil NO_3-N content to 0-30 cm depth immediately before grazing averaged 21 and 12 kg ha^{-1} for experiment 1 and 2, respectively. Sixty days after grazing, soil NO_3-N in the no catch crop plots were 49 and 40 kg ha^{-1} for experiment 1 and 2, respectively (0-30 cm) (Figure 6.1), indicating large increases in available soil NO_3-N in the absence of catch crops.

The ability of catch crops to reduce nitrate leaching potential was determined by measuring the difference between the soil NO_3-N content to 120 cm between catch crop and no catch crop plots. Catch crops in experiment 1 reduced the soil NO_3-N content at all depths compared with the no catch crop control treatment (Table 6.4 and Figure 6.1). There was significantly less soil NO_3-N in catch crops plots than no catch crop plots at 0-

30 and 30-60 cm after 30 days, and at all depths 60 days after the seeding of catch crops. Further, barley and oilseed radish were equally effective at reducing soil NO_3-N content compared to no catch crop plots in experiment 1. The ability of catch crops to reduce NO_3-N leaching has been shown previously by a number of studies (Hansen and Djurhuus, 1997; Thorup-Kristensen et al., 2003; Berntsen et al., 2006).

A significant species x time interaction in experiment 1 showed that extraction of soil NO_3-N by barley and oilseed radish was progressively stronger as time passed. One month after the catch crop seeding in experiment 1, oilseed radish and barley plots contained 36 and 28 kg ha^{-1} less NO_3-N than the no catch crop plots at 0-120 cm, respectively (Table 6.4 and Figure 6.1). This difference increased to 53 and 62 kg ha^{-1} 60 days after seeding catch crop (Table 6.4 and Figure 6.1). The change in soil NO_3-N is related to N uptake by the catch crops. In experiment 1 oilseed radish and barley biomass samples taken 60 days after seeding contained 58 and 55 kg ha^{-1} of N respectively (Table 6.3). Clearly, catch crop biomass N uptake explains the decrease in soil NO_3-N caused by the catch crops. A long-term organic catch crop study in Denmark reported lower soil N values than the present study (Sapkota et al., 2012). Fodder radish and ryegrass reduced soil N (NO_3 + NH_4) by 20 and 15 kg ha^{-1}, respectively. Similar to the present study, soil N differences in the Danish study were explained by catch crop N uptake differences. For example, fodder radish and ryegrass biomass N uptake were 45 and 22 kg N ha^{-1}, respectively.

Lower NO_3-N capture by catch crops in experiment 2 was attributed to lower biomass productivity than in experiment 1 (Table 6.3 and Figure 6.1). In experiment 2, at 50 days after catch crop seeding, oilseed radish and barley plots contained 5 and 19 kg ha^{-1} less NO_3-N in the 0-30 cm soil depth than the no catch crop plots (Table 6.4 and Figure 6.1). While barley took up soil NO_3-N that was apparently available, oilseed radish took up more NO_3-N than what was apparently available. For example, N uptake by barley biomass (19 kg ha^{-1}) explains the soil NO_3-N content difference between the control (40 kg ha^{-1}) and barley (21 kg ha^{-1}) plots (0-30 cm). However, soil NO_3-N content difference between control and oilseed radish plots (5 kg ha^{-1}) is less than oilseed radish biomass N uptake (15 kg ha^{-1}). It may be speculated that oilseed radish has the ability to uptake N compounds other than NO_3-N (i.e. NH_4-N). Another explanation could be related to greater rooting depth of oilseed radish compared to monocots (Thorup-Kristensen, 2001). For example in Denmark, while forage radish roots reached a depth of 110 cm by October 8, perennial ryegrass roots reached only 60 cm (Munkholm and Hansen, 2012). This once again supports the observation that oilseed radish has a better ability to uptake soil N than some monocots (Laine et al., 1993). However, at other depths no significant soil NO_3-N content differences between the barley and oilseed radish were observed.

When selecting a catch crop, N uptake ability of the catch crop may be considered to be more important than biomass producing ability. Vos and Van der Putten (1997) showed that N concentration of catch crops did not explain the catch crop biomass production especially when biomass was less than 1000 kg ha^{-1}. Generally, as the amount of biomass increased, N concentration decreased. Results of experiment 1 are in agreement with their observations. Although oilseed radish produced less biomass than barley, oilseed radish was able to take up similar amounts of N as barley in experiment 1. However, soil in the barley plots in experiment 2 contained less NO_3-N than the oilseed plots at 0-30 cm depth.

The present study is unique because catch crops were established after the N build-up phase (i.e. green manure), rather than after cash crop production, as commonly practiced. Catch crops seeded after grazing green manures (high NO_3-N availability) may behave differently than catch crops that are seeded under low N situations. Catch crops seeded under high N fertility situations may produce greater biomass than when seeded in low fertility situations (Vos and Van der Putten, 1997). Under low N fertility, catch crops can also immobilize soil N and negatively affect cash crop production in the following year (Schroder et al., 1997).

There were no significant differences in soil NO_3-N between no-till and conventionally seeded crops in either experiment. The absence of significant catch crop species by seeding management interactions indicated that both catch crops responded similarly to tillage in terms of NO_3-N uptake. Highly available NO_3-N after grazing of green manures was taken up by both catch crops under both tillage managements with similar efficiency. Once again, grazing of green manures appeared to be an effective strategy to improve N availability in reduced till organic systems.

Treatment effects on soil NO_3-N (0-120cm) were tested on different dates over the study period providing the opportunity to better understand response over time. Results showed significantly more NO_3-N in the no catch crop compared to catch crop treatments in the catch crop year (Table 6.4, Figure 6.2). At time of wheat seeding, the following year, treatment differences still remained. Therefore, lower N by catch crops was maintained through the winter and early spring. After wheat harvest, on the other hand, soil NO_3-N levels were higher in the catch crop treatments compared with the control treatment (Table 6.4, Figure 6.2). These observations also provide evidence that N mineralization from catch crop biomass was slow and may not have been in synchrony with wheat N requirements, and this may explain greater availability of N after wheat harvest in the catch crops compared with the control treatment. One possible explanation is that wheat may have taken up more N in the no catch crop system than the catch crop system, leaving more N in the soil in the catch crop system. For example, in experiment 1, soil NO_3-N (0-120 cm) in the no catch crop treatment after wheat harvest was 17 and 13 kg ha^{-1} less than oilseed radish and barley plots, respectively (Figure 6.2). This may be attributed to slow mineralization of organic N in catch crop biomass not being taken up by wheat crop in synchrony (Ladd et al., 1983; Mohr et al., 1998a), as well as, faster depletion of readily available soil NO_3-N from urine in no catch crop plots by the wheat crop (Cicek et al., 2014b). In experiment 2, there were no significant differences between treatments. Oilseed radish and no catch crop plots acted similarly in experiment 2.

In their meta analysis Tonitto et al. (2006) found that, in general, legume-based systems must provide around 110 kg ha^{-1} of N for subsequent crop yields to be similar to the conventional fertilized systems. In the present study, total soil NO_3-N content in the spring before the wheat production were well below 110 kg ha^{-1} in plots where catch crops were grown (Figure 6.2). Soil NO_3-N content in no catch crop plots, on the other hand, were 95 and 105 kg ha^{-1}, respectively, for experiments 1 and 2. Therefore, although successful in capturing soil NO_3-N, catch crops in this study reduced available N at seeding time below the threshold for optimum wheat production. A possible strategy to facilitate both catch crop production (for environmental protection) and optimum wheat production may be to graze the catch crops in late autumn. Grazing would be expected to release biomass bound N faster than soil decomposition of catch crop biomass during the cold winter months.

Soil NO_3-N after fall rye harvest was not affected by any of the treatments (data not shown). Total soil NO_3-N (0-120 cm) was very low (15 kg ha^{-1}) for all treatments, indicating that soil N was equally depleted in all treatments.

Wheat and fall rye N uptake and productivity

Wheat productivity was negatively affected by the presence of catch crops in both experiments. In experiment 1, biomass production at stem elongation, anthesis and maturity and wheat yield were significantly reduced by catch crops (Figures 6.2 and 6.3). In experiment 2, biomass production at maturity and wheat grain were significantly reduced by catch crops. Therefore, the hypothesis that productivity of wheat would be greater when grown in catch crop plots was rejected. Among the two catch crops tested, wheat grown in barley plots was most negatively affected, producing significantly less biomass than wheat grown in oilseed radish and no catch crop plots in experiment 1 (at stem elongation and anthesis) and in experiment 2 (at maturity). Wheat yields were also lower in barley compared with oilseed radish plots in both experiments (significant only in experiment 1; Figure 6.4). Lower wheat productivity in barley plots suggests that N release from barley biomass was slower than radish and did not meet wheat N demand.

A series of long-term experiments conducted at three locations with varying soil, weather and fertility conditions across Denmark showed that the response of spring cereals to catch crops are species (catch crop and cash crop), management (manure, rotation), and soil type (sandy loam, coarse sand) dependent (Olesen et al., 2007; 2009; Doltra and Olesen, 2013). While oat yields and grain N were increased by inclusion of catch crops, barley yields were not affected. The authors concluded that slower early vegetative development of oat compared to barley, made it possible for the oat crop to better synchronize the N uptake with the N release from the catch crops. It appears that selection of catch crops with fast N release properties may improve cash crop productivity.

In the present experiment it was observed that oilseed radish released N faster than barley catch crop. In experiment 1 wheat N uptake at stem elongation was significantly higher in oilseed radish plots than barley plots (Figure 6.3). Similarly, in experiment 2, wheat biomass production at maturity was higher in oilseed radish plots than barley. Although oilseed radish appeared to be more promising catch crop than barley in terms of providing timely N release to cash crops, wheat in no catch crop plots took up more N and produced more biomass than oilseed radish plots.

Although both catch crops performed well in terms of biomass production and N uptake, the N release from the catch crop biomass was not in synchrony with the wheat N uptake for optimum productivity. Both in experiment 1 and 2, the wheat biomass difference between the treatments (i.e. catch crops vs. no catch crops) progressively increased from stem elongation to maturity. By maturity, wheat grown in the no catch crop treatment had more biomass than wheat grown in both catch crop treatments (Table 6.5, Figure 6.3). Similarly, N uptake of wheat at maturity was significantly more in no catch crops especially in experiment 1 as result of greater soil NO_3-N availability. Future investigations should examine faster decomposing catch crops than barley and oilseed radish. For instance, in Ontario, Vyn et al. (2000) found that compared to legume red clover, which increased corn productivity, radish, fall rye or oat catch crops had negative or no effect on corn productivity.

Tillage management of catch crops did not affect wheat productivity (Table 6.5). All catch crop plots were tilled prior to wheat establishment, hence, wheat was sown into tilled plots. Nevertheless, the present study illustrated that reducing tillage during catch crop production had no negative effect on wheat productivity. Absence of tillage x catch crop species interaction on wheat productivity also confirmed that regardless of the catch crop species, reducing tillage had no effect on wheat productivity.

There was also no effect of tillage management or catch crops on fall rye productivity (data not shown). Fall rye biomass production ranged from 6290 to 7670 kg ha^{-1} and grain yield ranged from 3160 to 3640 kg ha^{-1}. Bullied et al. (2002) also reported no effect from a low N single year green manure to second grain crop. Similar to wheat year, N "stored" in catch crop biomass did not benefit fall rye productivity. Expectation would have been that biomass stored N would be released during the fall rye year and increase fall rye productivity compared to no catch crop treatment (Hoyt, 1990). Perhaps some of the N in the biomass transformed into more stable organic N fractions and became less available.

Strategies to improve N benefit from catch crops

The present study illustrated that extra N made available by grazing of green manures can be captured by catch crops but N release from catch crops was not in synchrony with the demands of a following wheat crop. Even though oilseed radish released N slightly better than barley, it appeared that the slow mineralization of catch crop biomass was the reason. Including low C:N ratio catch crops or legume/grass mixtures and manure addition during the catch crop phase have been suggested as ways to increase the speed of mineralization from catch crop residues. For instance, in France, N mineralization from a low C:N (12.8) mustard catch crop was faster than radish and ryegrass catch crops with higher C:N ratios; 17 and 28.3 respectively (Constantin et al., 2011). In Denmark, increased ryegrass proportion in legume/grass catch crop mixtures, decreased the N release rate (Doltra and Olesen, 2013). Another strategy to increase N availability from catch crops is grazing the catch crops in late autumn after they have "secured" the N in their biomass, which has not been investigated by earlier studies. Since grazing of catch crops may release more N to the system, such management strategy should only be employed in regions with cold winters and low risk of late autumn and spring runoff.

6.5 Conclusions

This study was conducted under contrasting growing seasons. When precipitation was high, catch crops produced a high amount of biomass and reduced soil NO_3-N loading. When precipitation was low, catch crops produced little biomass and had a limited effect on soil nitrate. Although catch crops were successful at capturing soil NO_3-N, productivity of wheat grown after catch crops was much lower than wheat grown in the no catch crop treatment. Nitrogen captured in catch crop biomass was not released in synchrony (i.e. slower) with the wheat demand. Between the catch crops, oilseed radish released N faster than barley.

Catch crops were able to reduce soil NO_3-N loading up to 120 cm depth when conditions were favorable (above-average precipitation) for catch crop biomass production. Hence, catch crops reduced the risk of leaching when precipitation was above average. In a dry year, catch crops did not reduce soil NO_3-N content as a result of lower biomass productivity. Under such dry conditions, catch crops may be considered as organic matter building, cover or forage crops with less utility in N capture.

Cultivating soil before catch crop seeding did not offer any N uptake or biomass accumulation advantages over no-till seeding into grazed green manure residue. Nitrogen uptake and biomass productivity of catch crops were similar under no-till and conventional seeding. The present study, therefore, provided strong evidence for possibility of reducing tillage in organic crop-livestock integrated systems because of greater N availability after grazing.

Mineralization of N from catch crop biomass appeared to be very slow. Future studies should consider leguminous species with higher mineralization rates than oilseed radish or barley. Legumes also add more N to soil, thereby improving the potential N benefit to the following crops. Grazing of catch crops should also be considered for timely and improved N release from catch crops. It may be possible to avoid autumn and spring tillage to mineralize N for wheat if catch crops are grazed in late autumn.

Tables and Figures

Table 6.1. Average monthly growing season air temperatures and precipitation for Carman, Manitoba, Canada from 2010 to 2012.

	Air Temperatures				Precipitation			
	2010	2011	2012	Average*	2010	2011	2012	Average*
April	8.7	4.5	6.2	4.2	35	44	19	42.5
May	11.6	10.4	12.1	12.5	159	72	61	52.7
June	16.3	16.7	17.7	16.9	63	59	86	72.8
July	19.6	20.3	21.9	19.4	48	38	28	69.1
August	18.7	19.3	19.0	18.2	138	12	47	65.5
September	11.8	14	12.5	12.2	107	65	3	49
October	8.3	8.2	4.2	5.5	57	8	85	34
Total					607	297	328	386

*from 1961 to 1990

Table 6.2. Dates of field operations for experiments 1 and 2.

Experiment	Seed green manure	Graze green manures	Seed catch crops	Terminate catch crops	Wheat seeding	Wheat harvest	Fall rye seeding	Fall rye harvest
1	June 4, 2010	August 8, 2010	August 9, 2010	Oct 21, 2010	May 20, 2011	August 25, 2011	Sept 1, 2011	July 31, 2012
2	June 8, 2011	August 20, 2011	August 21, 2011	Oct 11, 2011	April 26, 2012	August 9, 2012	-	-

Table 6.3. Effect of catch crop species (barley and oilseed radish) and seeding management (direct seeding and conventional seeding) on catch crop dry matter biomass production, daily growth rate, N uptake and N concentration for experiments (Exp) 1 and 2.

	Growth rates		Biomass		N uptake		N concentration	
Treatments	Exp 1	Exp 2	Exp 1	Exp 2	Exp 1	Exp 2	Exp 1	Exp 2
Species	kg ha^{-1} d^{-1}		--------------------kg ha^{-1}-----------------				--------%---------	
Oilseed radish	36b	7	2620b	364	58	15	2.4a	4.2a
Barley	47a	10	3438a	551	55	19	1.6b	3.5b
Management								
Direct seeding	38	7	2788	362	56	13	2.1	3.8
Conventional seeding	45	10	3269	554	57	20	1.9	3.9
Analysis of Variance	--*P* value--							
Species (S)	0.0198	0.0814	0.0155	0.0942	0.5313	0.1659	0.0011	0.0493
Management (M)	0.4038	0.1487	0.3931	0.1282	0.9067	0.1377	0.1838	0.5428
S x M	0.1835	0.295	0.1685	0.3438	0.1877	0.7145	0.4127	0.1261

Within columns of same main effect, numbers followed by the same letters are not significantly different according to Fisher LSD test ($p < 0.05$).

Table 6.4. Highlights of analysis of variance for the effect of catch crop species (no catch crop, barley and oilseed radish), seeding management (direct seeding and conventional seeding) and time (September 2010, October 2010, May 2011 and September 2011 for experiment 1, and October 2011, May 2012 and September 2012 for experiment 2) on soil NO_3^- -N content at depths of 0-30, 30-60, 60-90 and 90-120 cm for experiments 1 and 2.

	Soil NO_3^- -N content				
Source of variation	0-30cm	30-60cm	60-90cm	90-120cm	Total (0-120cm)
Experiment 1	---------------------------P value---------------------------------				
Species (S)	<.0001	<.0001	0.0153	0.001	<.0001
Management (M)	0.3619	0.9806	0.4187	0.9759	0.9154
Time (T)	<.0001	<.0001	<.0001	<.0001	<.0001
S x M	0.9045	0.5501	0.3578	0.300	0.9006
S x T	<.0001	<.0001	0.0005	0.0125	<.0001
M x T	0.8728	0.4061	0.3682	0.4426	0.6051
S x M x T	0.0888	0.4372	0.1451	0.6614	0.129
Experiment 2					
Species (S)	0.0003	0.0094	0.6448	0.2618	0.0026
Management (M)	0.6929	0.6943	0.5901	0.3972	0.864
Time (T)	<.0001	<.0001	<.0001	<.0001	<.0001
S x M	0.1011	0.7413	0.9198	0.8374	0.3655
S x T	0.3628	0.5822	0.9111	0.9905	0.5467
M x T	0.0553	0.5404	0.6739	0.787	0.3533
S x M x T	0.8399	0.9891	0.9938	0.8838	0.9234

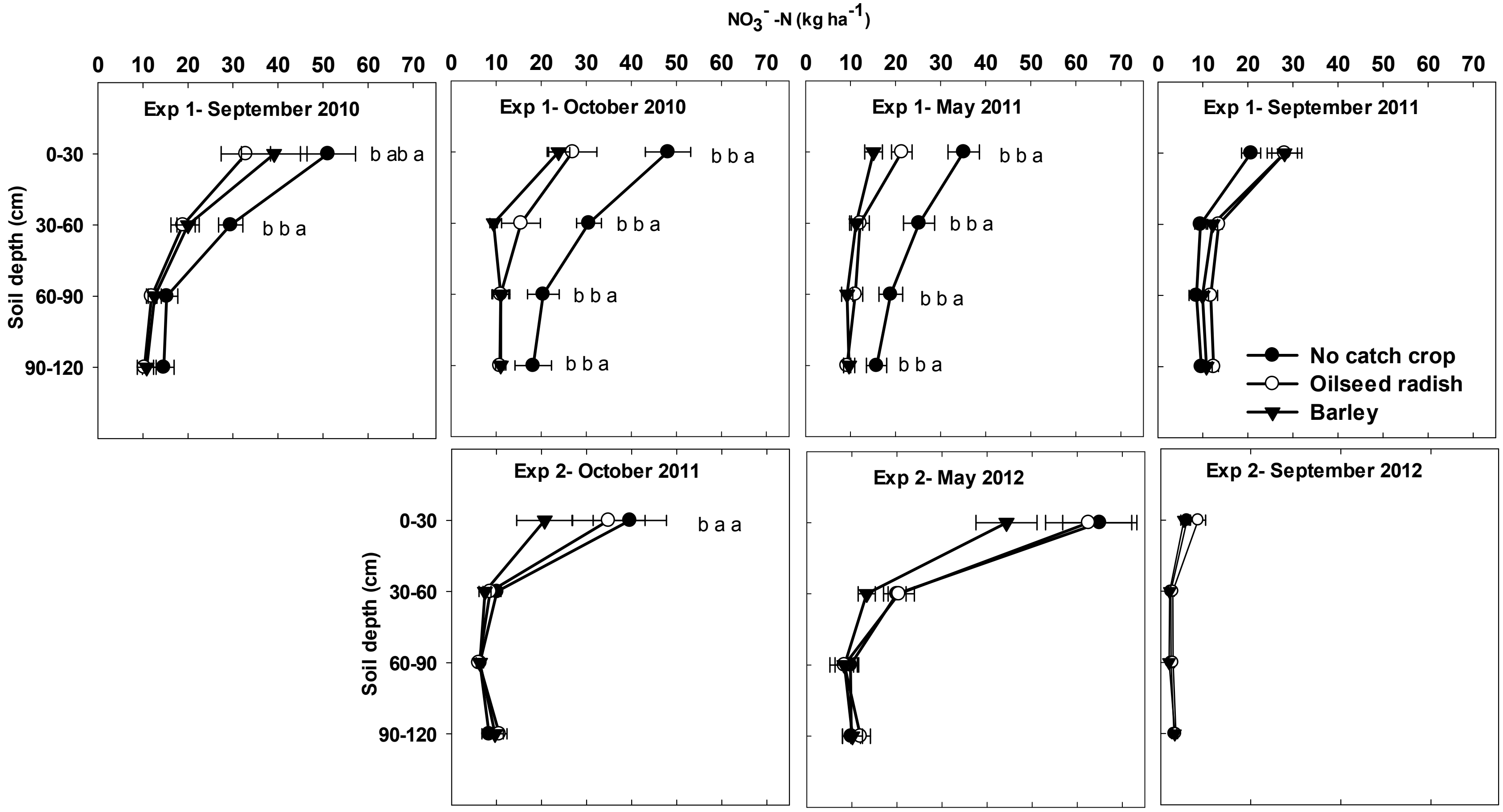

Figure 6.1. Soil nitrate as affected by catch crop species (no catch crop, barley and oilseed radish) at depths of 0-30, 30-60, 60-90 and 90-120 cm over two years for the experiments 1 and 2. Please refer to Table 6.4 for highlight of analysis of variance of soil nitrate as affected by species and management. Horizontal bars are standard errors. Within each depth for species main effects, points followed by the same letters are not significantly different according to Fisher LSD test ($p < 0.05$).

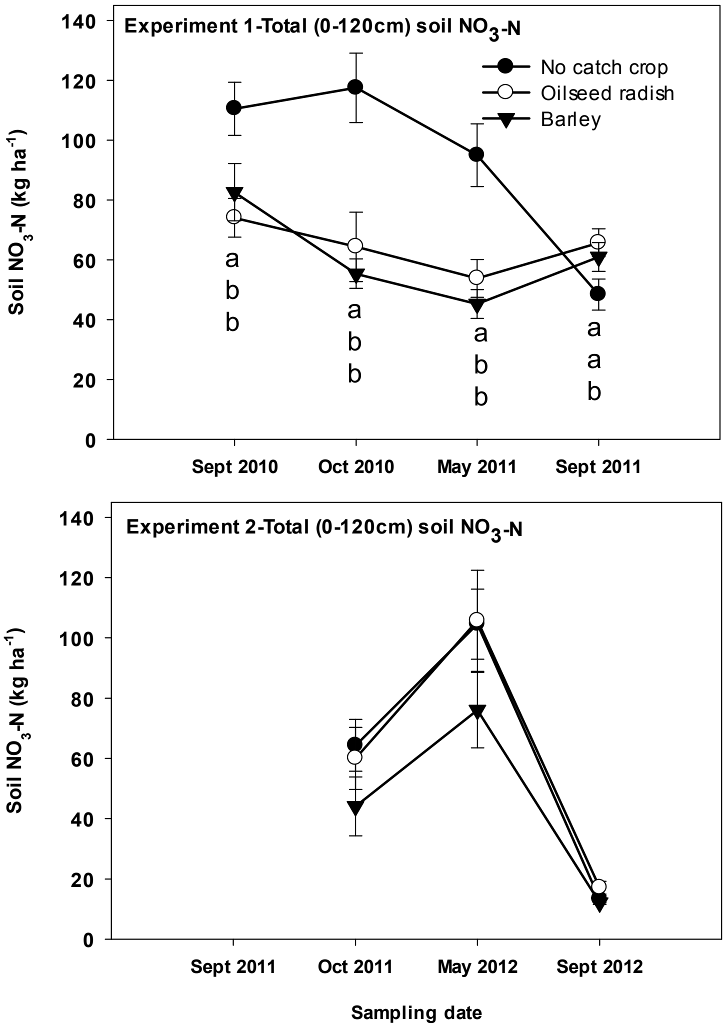

Figure 6.2. Total (0-120 cm) soil nitrate as affected by catch crop species (no catch crop, barley and oilseed radish) over two years for the experiments 1 and 2. Please refer to table 6.4 for highlight of analysis of variance of soil nitrate as affected by species and management. Vertical bars are standard errors. Within each date for species main effects, points followed by the same letters are not significantly different according to Fisher LSD test ($p < 0.05$).

Table 6.5. Highlights of analysis of variance for the effect of catch crop species (no catch crop, barley and oilseed radish), catch crop seeding management (direct seeding and conventional seeding) and time (stem elongation, anthesis and maturity stages) on wheat dry matter biomass, biomass N concentration, biomass N uptake for experiments (Exp) 1 and 2.

	Dry matter		N concentration		N uptake	
Source of variation	Exp1	Exp 2	Exp1	Exp 2	Exp1	Exp 2
Wheat biomass	------------------------------------P value------------------------------------					
Species (S)	<.0001	0.0823	0.0247	0.0499	0.0004	0.0956
Management (M)	0.3188	0.3944	0.5972	0.673	0.5181	0.1619
Time (T)	<.0001	<.0001	<.0001	<.0001	<.0001	0.0023
S x M	0.6316	0.8185	0.2865	0.313	0.4153	0.4575
S x T	0.9823	0.9058	0.3784	0.5697	0.537	0.7583
M x T	0.4718	0.6283	0.8313	0.2489	0.6321	0.9587
S x M x T	0.384	0.808	0.4299	0.8189	0.525	0.9923
Wheat grain						
S	0.0024	0.0435	0.1407	0.1950	-	-
M	0.4077	0.1719	0.8735	0.8788	-	-
S x M	0.8394	0.9879	0.1211	0.0133	-	-

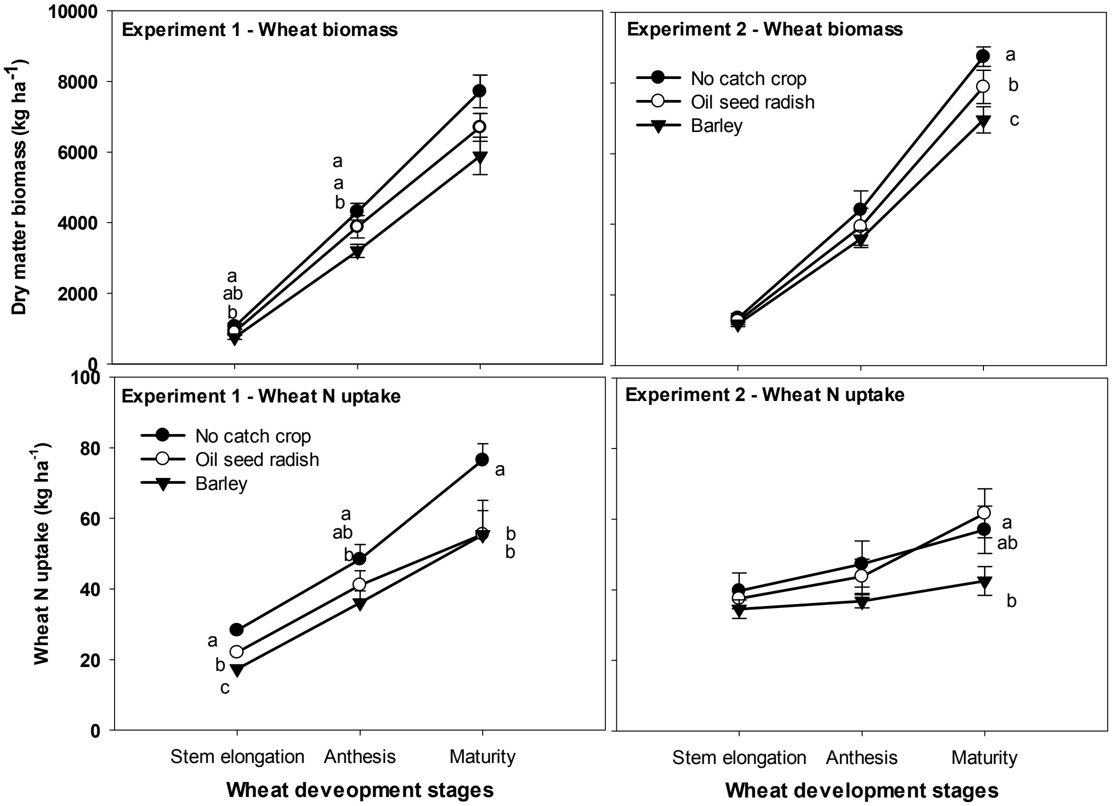

Figure 6.3. Effect of catch crop species (no catch crop, barley and oilseed radish) on wheat dry matter biomass and N uptake at stem elongation, anthesis and maturity development stages for experiments 1 and 2. Please refer to Table 6.5 for highlight of analysis of variance of soil nitrate as affected by species and management. Vertical bars are standard errors. Within development stage for species main effects, points followed by the same letters are not significantly different according to Fisher LSD test ($p < 0.05$).

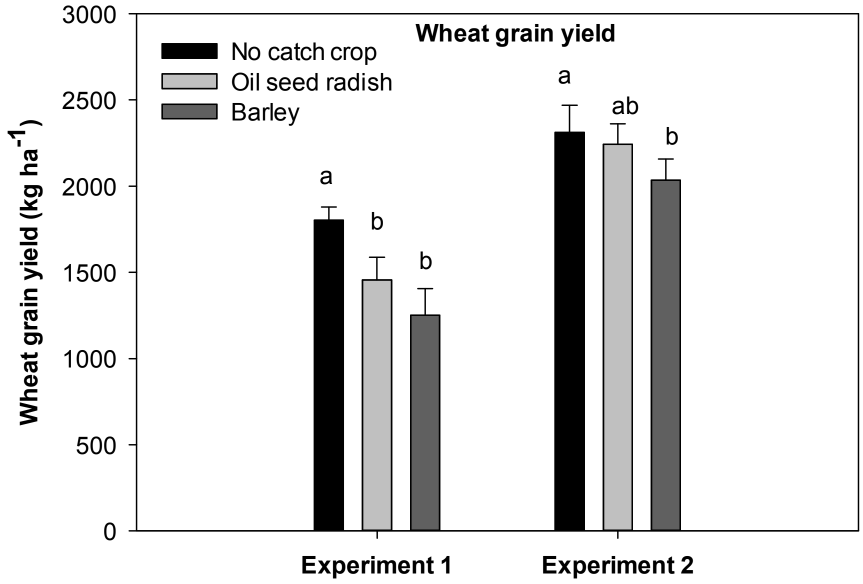

Figure 6.4. Effect of catch crop species (no catch crop, barley and oilseed radish) on wheat grain yield for experiments 1 and 2.

7. GENERAL SUMMARY

Organic agriculture is often criticised for low productivity, low N availability and dependence on excessive tillage compared to conventional and no-till systems. Legumes (i.e. green manures) and animal manures are the primary source of nutrients in organic systems. Although the ecological and environmental superiority of legume-based systems compared to synthetic fertilizer based systems has been widely shown, adoption of legume-based systems on organic farms is still low. Among the reasons for this low adoption are: i) when green manures are grown in short season environments such as western Canada, cash crop production is compromised and farmers incur economic opportunity loss, and ii) the perception that green manures cannot provide sufficient N for cash crop production. There is an urgent need to design legume-based organic systems with improved N availability for grain production and a reduced reliance on tillage.

A series of field experiments were established to investigate the prospect of optimizing N benefits from green manures in organic agriculture. The objectives of these studies were to identify green manure species and green manure management options to maximize N benefit to following cash crops and explore the opportunities to reduce tillage during the green manure phase of the rotation. Four green manure systems were tested including double-cropped green manures, relay-cropped green manures, full season green manures, and catch crops after grazed full season green manures. Three green manure management options were tested; soil incorporation with tillage, grazing and no-till, but not all these options were tested with every experiment. A total of 10 green manure species and 3 green manure mixtures were tested under different systems and managements. None of the systems tested in the present study had been previously investigated in Western Canada. Information generated from the present study has, therefore, immediate practical, as well as, theoretical implications for agroecosystem management in temperate regions.

The greatest N contribution to the cropping system occurred when full season green manures were grown and utilized by grazing. Among these full season species, an intercrop pea/oat and hairy vetch supplied the greatest amount of N to the system. The lowest N availability was observed in a system when double crops were managed in a no-till system. Double did not produce adequate biomass resulting in low levels of biologically-fixed N. Among the relay and double crops tested, relay-cropped red clover and double-cropped pea were the greatest biomass producers and N suppliers. Reduced tillage-induced N mineralization decline was offset when red clover, sweet clover or pea were grown as relay or double crops, since these legumes were able to produce more N. Catch crops after grazing green manures, regardless of the species, significantly reduced N leaching risk compared to no catch crop treatment, but also reduced following wheat productivity due to N sequestration. Catch crop biomass productivity and N uptake, soil NO_3-N, and wheat productivity were similar in direct seeded and conventionally seeded plots.

7.1 Green Manure Systems and N Availability

The effect of grazing green manures on N availability compared to soil incorporation was investigated in full season green manure systems. Grazing full season green manures, compared to soil incorporation, significantly increased soil NO_3-N content, and the increase was confined to the 0-30 cm level, where it could be easily accessed by a following crop. Soil nitrate content was greater when full season pea/oat mix was grazed compared to oat. On average grazing increased soil NO_3-N by 25% (Figure 7.1). Higher availability of N after grazing of green manures did not increase wheat or fall rye yields compared to soil incorporation. However, wheat biomass N uptake was higher in grazed plots compared to ungrazed ones and this difference was greatest in grazed hairy vetch and pea/oat plots. This suggests that grazing did indeed improve N availability to the following crop and that the response was greatest in green manure systems that supplied higher amounts of N.

Importantly, there were no declines in wheat or fall rye productivity grown after green manures when grazed versus tilled. Therefore, grazing allowed the full N benefit from the green manure to be captured, with the additional benefit of livestock productivity (i.e. 3000-6000 kg ha^{-1} of forage) during the green manure year. There have been no studies in temperate regions that reported on using grazing to manage green manures. The standard practice for green manure management is to incorporate them into soil. The present study is the first study to investigate the grazing of green manures in western Canada. Only a few studies were conducted in warmer areas (i.e. Iowa and Georgia) where winter cover crops can be grown and grazed. These studies reported either modest increases in productivity or no negative effects of grazing compared to ungrazed systems.

The catch crop experiment investigated the capture and release of N by barley and oilseed radish after green manure grazing. N availability after green manure grazing was strongly modified by barley and oilseed radish catch crop growth. Both catch crops were effective at capturing N made available by grazing, but release of N from catch crop biomass was not in synchrony with the wheat demand, resulting in lower wheat yields where catch crops were used. Using low C:N ratio catch crops or legume/grass mixtures and grazing of catch crops have been suggested as ways to increase the speed of mineralization from catch crop residues. Legumes may add more N to soil, thereby improving the potential N benefit to the following crops. However, legumes grown in N rich soils may not fix as much N_2 as they would in N poor soils. Therefore, grazing of catch crops maybe a more effective strategy for timely and improved N release from catch crops and this concept requires further research.

Relay and double crop experiments explored the possibility of adding N to a system during the winter grain phase of the organic rotation. Nitrogen benefit to wheat from relay and double crops was not consistent across species, but wheat yield generally increased with increasing green manure legume biomass production. Among the green manure species tested in these relay and double crop studies, sweet clover, red clover and pea produced the greatest benefit to wheat.

The results of the present study made it possible to construct a model where potential biomass productivity and N supply of various green manures systems and management options were depicted (Figure 7.1). The positioning of the green manure systems in terms of biomass productivity was based on the results of the present study. Nitrogen supply is

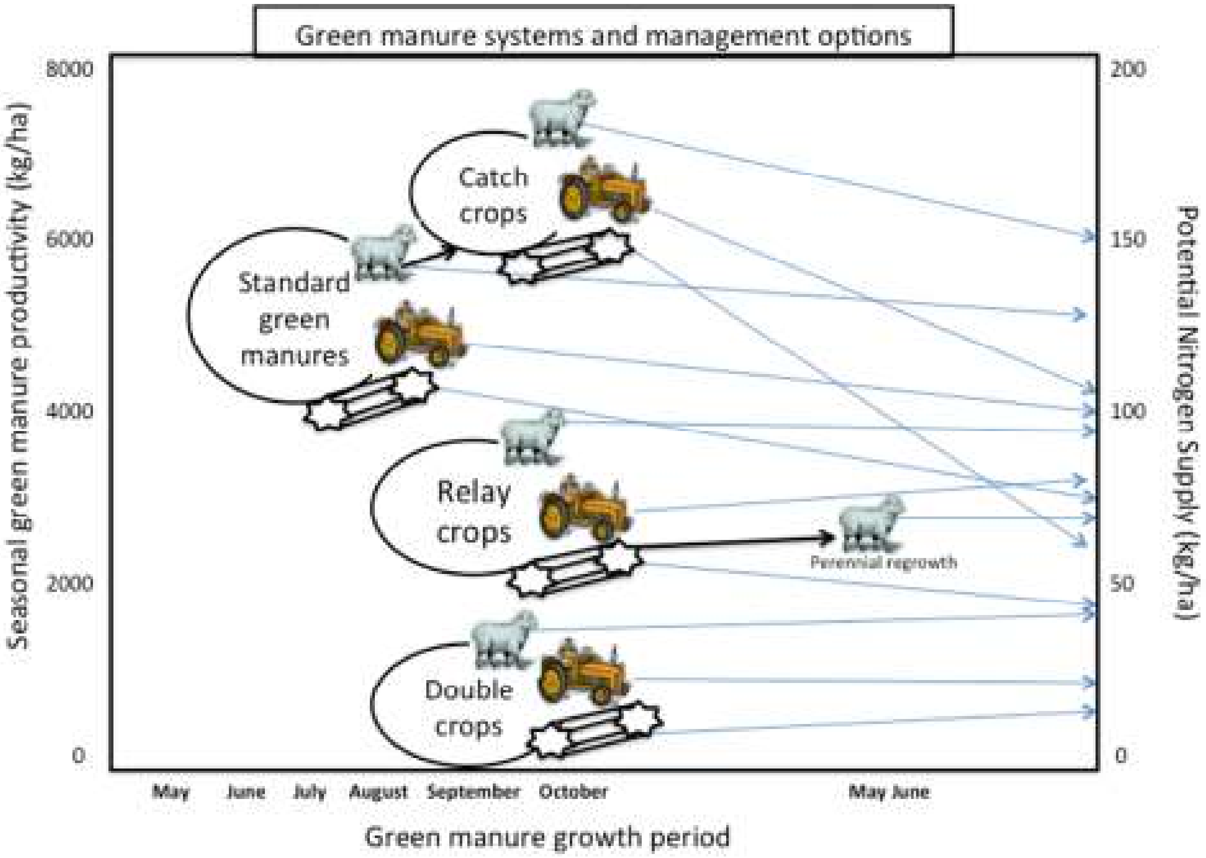

Figure 7.1. Overview of green manure systems (i.e. double, relay, standard and catch crops), and management options (i.e. grazing green manures [icon:sheep], incorporation of green manures [icon:tractor] and no-till green manures [icon: roller]) effect on seasonal green manure biomass productivity and potential nitrogen benefit. Standard green manure management option was incorporation of green manures, which was assumed to provide 2.5% of N per 1000 kg ha^{-1} of biomass (Peoples et al., 1995). Grazing was assumed to increase N availability by 25% (Cicek et al., 2013). No-till management of green manures were considered to reduce N availability (Vaisman et al., 2011). Catch crop biomass productivity was assumed to be between 1500 to 2500 kg ha^{-1}. Therefore, position of catch crops on the model indicates cumulative biomass production (i.e. standard green manures + catch crops) within a season.

a function of biomass productivity and the management. Arrows from the interaction of green manure systems and management indicate the potential N supply, which are based on the present, as well as, earlier studies that investigated such interactions. This model does by no means illustrate all the possible green manure systems management options, but it does provide a good framework to explore other possible green manure systems.

The present experiment employed ruminants only in one green manure system and reported positive results. As indicated in the Figure 7.1 ruminants can potentially be included in various phases of the crop rotation and potentially increase N supply. All late season green manures tested in this study (double, relay and catch crops) have the potential to be grazed. Grazing late season green manures would significantly increase the N benefit to the following cash crop. When winter hardy, perennial relay crops are not terminated in the autumn, regrowth from these crops in spring can be grazed. Such early season N availability from grazing may significantly increase yield of crops such as wheat and barley, which has high N requirements at early developmental stages. Future studies can investigate grazing of early and late season green manures for improved N supply.

7.2 Tillage and N availability

Reduced tillage was compared with more intensive tillage in relay and double crop experiments, as well as in the catch crop experiments. In the double and relay crop study, reduced tillage involved direct seeding of green manures into fall rye stubble thereby delaying tillage until spring. In the catch crop study, reduced tillage meant direct seeding catch crops into grazed green manure residues.

Results from the double and relay crop experiments provided evidence that adequate biomass production by clovers and pea were effective at offsetting reduced tillage-induced N mineralization reduction. The present study could not establish the exact amount of legume biomass that is needed to achieve no-tillage with no wheat productivity penalty (i.e. offset the lower N mineralization), but from the available data it appeared that as little as 500 kg ha^{-1} of legume biomass was sufficient. Without the legume N from these cover crops, eliminating fall tillage almost always reduced N supply to the following wheat crop. Therefore, this study provided evidence that the presence of a late-season legume cover crop may facilitate reduced tillage in organic farming by offsetting the N limitations that occur when fall tillage is eliminated. Further research is needed to establish the amount of critical cover crop biomass needed to reduce tillage in organic late season cover crop production.

In the catch crop experiment, tillage management did not have any effect on catch crop biomass productivity and N extraction. Cultivating soil before seeding did not offer any advantage over direct seeding of catch crops into grazed green manure residue. This provided additional encouraging evidence that tillage can be reduced in organic systems when grazing is used as management. While the experiment was not established to investigate the underlying reasons, it appeared that rumen processing of the green manures improved N availability, and potentially offset any reduction in N from the direct seeded catch crop system. This provided strong evidence for considering grazing as a management tool to reduce tillage in organic agriculture.

7.3 Green Manure Biomass Productivity, Weed Competition and Utilization

The present study provided valuable information on biomass productivity, weed competition and utilization of various green manures under organic management. Indeed, there is information on biomass productivity of full season green manures in western Canada under conventional management. However, information for organic production is scarce, particularly for late season green manures, which are still novel in Canadian agriculture. It is important to test green manures under organic management because, unlike in conventional systems, weeds are always present in organic systems. Most green manures are composed of legumes or mixtures containing legumes and, legumes are known to be weak competitors with weeds. This begs the question as to which green manure species or mixtures competed best with weeds and produced sufficient biomass to provide N benefit to the following crops.

The present study provided some answers to this question. Among the number of green manure species tested only a few provided sufficient N to the following crop, indicating the need for research on novel green manures and mixtures for the future. The greatest biomass producing green manures were hairy vetch, pea/oat, and sweet clover, producing approximately 5000 kg ha^{-1} of biomass. Pea/oat and hairy vetch were the most weed competitive species on average contained less than 15% weed biomass. This was the first study reporting on the spring seeded hairy vetch productivity in western Canada. Hairy vetch is becoming more popular among organic growers and some researchers are exploring no-till organic systems using hairy vetch and its mixtures with other crops as green manure mulch. The least weed-competitive crops were soybean, lentil and the species mixture. Soybean and lentil forage biomass contained 30 – 70% weed biomass.

Weed biomass and competition after the green manure phase (i.e. in wheat) was not investigated in the present study. Management of green manures can have direct impact on weed populations and dynamics. Reduced till managed double and relay crops may reduce weed competiveness by providing early season mulch cover. On the other hand, grazing may increase weed competitiveness by improving N availability to weeds as well as the crop. Weed dynamics as influenced by late season green manure management and grazing of green manures requires further investigation.

Weed dynamics during late season green manure growth are different than weed issues during full season green manures. While perennials are the main issue in late season crop production, fast growing summer annuals are the primary weeds competing with full season green manures. Late season green manures have access to fewer growing days and precipitation than full season green manures to produce biomass. Nevertheless, double-cropped pea and relay-cropped red clover produced approximately 900 kg ha^{-1} and 2000 kg ha^{-1} of biomass, respectively. Both crops competed with weeds effectively, perhaps as a result of N limited conditions restricting weed growth. Overall, relay crops were more productive than the double crops. In the catch crop experiment, barley and oilseed radish produced 2000 kg ha^{-1} and 1500 kg ha^{-1} respectively. Catch crops also competed with weeds effectively. Therefore, late season green manures may be effective tools in reducing perennial weed competition in organic systems, because they are able to provide competition through their physical growth.

Selection criteria for annual forages in organic systems should include: i) sufficient dry matter biomass production for livestock, ii) nitrogen contribution to subsequent cash crops, iii) weed competitiveness, and iv) nutritional quality and palatability. Based on biomass productivity and utilization by sheep, pea/oat, hairy vetch and oat can be recommended as annual forages. Although the present study did not evaluate the grazing of late season green manures (i.e. double, relay and catch crops), they showed potential to extend grazing season and provide forage in times when forages are in limited supply.

Grazing of late season green manures or catch crops may improve N availability to the following crop but caution must be paid to potential gaseous N losses and N leaching. Gaseous N losses such as volatilization and denitrification increase with increasing temperatures. Since autumn temperatures in western Canada are very low, gaseous losses may not represent significant portion of N losses. Leaching of N in late season grazing systems will depend on the spring soil moisture conditions. Snowmelt during the spring may accelerate N leaching. Nitrogen losses under late season grazing systems requires further investigation.

8. DISCUSSION AND FUTURE RESEARCH OPPORTUNITIES

There is an urgent need to offer alternatives to the current paradigm of agriculture (IAASTD, 2009). Such alternatives must employ ecological means to manage soil-crop processes such as nutrient cycling. In the last century most nutrient management schemes involved modifying the amount, timing and placement of synthetic fertilizers and disregarded the role of ecological processes. Consequently, research on ecological-based nutrient management tools such as green manures and forages have received relatively little attention. The present study attempted to reduce the knowledge gap on ecological nutrient management in western Canada. It examined green manures and green manure management options as ecological means to regulate N flows in organic systems. The results provided strong evidence that green manures can be effective nitrogen suppliers in organic grain-based rotations. Green manure management appeared to be a potent modifying factor for green manure N mineralization. Managing green manures with grazing was the most effective method to improve N availability.

Grazing Green Manures Facilitate Reduced-Till Organic Systems

The present study examined N dynamics in a no-till system and provided strong evidence for improved N availability for no-till seeded crops after grazing green manures. Improved N availability in grazed green manure systems is a result of faster rumen digestion of green manure biomass compared to soil incorporated green manures. Figure 8.1 illustrates the theoretical decomposition rate of green manure biomass in terms of transformation of organic N to inorganic N. Slopes of the lines for rumen, mulch and soil incorporation of green manure in Figure 8.1 were constructed based on the observed rate of N availability (i.e. soil NO_3 and plant N uptake) in the literature. Microorganisms in the rumen transform organic N into inorganic N much faster than microbes in soil when green manures are mulched or incorporated. Symbiotic microorganisms within the rumen and digestive tract of ruminants are capable of cellulolytic activity to degrade plant cell walls and release N from within cells (Duncan and Poppi, 2008). This cellulolytic activity of microorganisms is more efficient in the rumen than the soil because of the favourable environment of the rumen as compared to the soil (i.e. constant pH, temperature, water availability, see page 34 for more detailed comparison).

Nitrogen mineralization in grazed systems is strongly affected by forage quality and quantity, as well as soil physical conditions (Schrama et al., 2013). There is information in the literature as to how the slope of the line for mulch and soil incorporation changes with management and species selection. Less information is available for how the slope of the line for the rumen may be influenced or manipulated by crop species or management. The present study provided some evidence that an increased proportion of legumes (i.e. low C:N material) increased the degree of the slope, but no conclusive evidence was found.

Figure 8.1 can be expanded to include other green manure management options and can provide a framework for construction of a decision-making tool for green manure management. Since it is expected that the slopes of the lines for management tools may be affected by species selection, a figure can be constructed for each species or group of species carrying certain traits (i.e. low C:N ratio). Future research projects can establish some of the N release patterns based on these management practices. Once sufficient data is available, Figure 8.1 can evolve into a decision making tool, where farmers can combine management and species selection to address specific end goals for their operations.

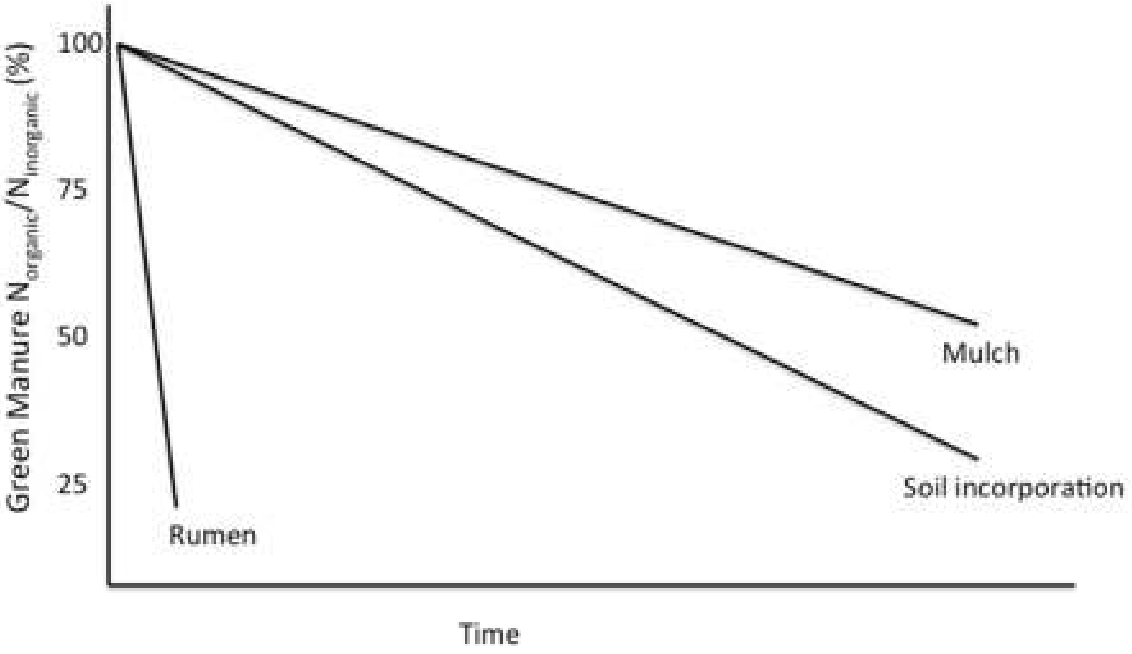

Figure 8.1. Conceptual model for green manure plant biomass decomposition in terms of N availability in the rumen, on soil (mulch) and incorporated into soil. Organic N to inorganic N ratio represents the transformation of biomass bound N (organic N) to plant available soluble N (inorganic N). Rates of decomposition of N from biomass were approximated from; Janzen and Schaalje (1992); Chesson (1997); Berg and Lawskowski (2006) and Cicek et al., (2014b).

Grazing management may also affect N mineralization rates. For instance, increasing grazing intensity can increase N mineralization and increase the productivity of following crops in long term perennial pasture crop rotations (Unkovich et al., 1998). In annual forage systems, the effect of grazing intensity on N mineralization has not been investigated. In the present study grazing intensity was standard among treatments (high stocking rate), therefore, different grazing intensity levels were not examined. Also, since grazing intensity may directly affect the amount of plant residue left on the soil surface, it may have implications for soil temperature and water holding capacity. Increased grazing intensities reduce plant cover insulating soils and increase soil temperatures, which in turn accelerate N mineralization (Schrama et al., 2013). As indicated by Carvalho et al. (2010), grazing intensity is one of the most potent factors effecting crop and animal productivity, as well as, soil quality. Crop and soil responses to varying levels of grazing intensity is much needed information towards the goal of achieving no-till organic production.

Figure 8.2 illustrates the possible pathways, processes and factors involved in achieving organic no-till production. Two of the most common pathways are mulching and grazing of green manures. There are a number of processes (i.e. green manure utilization, N mineralization) and factors (i.e. green manure and ruminant species, weeds), which can influence organic no-till crop production (Figure 8.2). Research is needed in most of these areas.

To achieve no-till through a grazing pathway requires selection or plant species for optimum N, knowledge of utilization rates for ground cover, ruminant species for best combination of plants and animals, and finally, information on grazing intensity, which determines the N mineralization, ground cover and animal performance (Figure 8.2). On the other hand achieving no-till through mulching green manures requires selection of plant species or mixtures for optimum decomposition rates, amount of biomass, and information on the implement types in terms of managing the green manure biomass (Figure 8.2).

Although it may appear from Figure 8.2 that grazing and mulching are mutually exclusive in reducing tillage, there may be opportunities to combine grazing with reduced tillage systems such as mulching. There is some information from Brazil on management of grazing intensity to achieve animal production, nutrient cycling, mulch and cash crop production. For instance, Brazilian researchers found that grazing animals must leave approximately 10 cm height of cover crops for no-till systems to accumulate soil organic carbon (Carvalho et al., 2010). When less than 10 cm of cover crop biomass was left after grazing, soil organic matter stocks decreased as a result of fast decomposition rates in this semi-tropical region. Leaving more than 10 cm (i.e. 20 and 30 cm) however, did not result in significantly higher soil organic matter accumulation than 10 cm cover crop biomass.

Similar information (i.e. grazing intensity and amount of green manure residue upon grazing) need to be established for temperate agroecosystems. Unlike the semi-tropical climate in Brazil where high precipitation (up to 2000 mm) and heat accelerates the decomposition of green manures (i.e. fast N mineralization), in temperate regions such as Canada, decomposition rates are slower and the amount of green manure biomass that can be retained for organic matter accumulation may be less. Also, leaving a large amount of biomass on the surface in temperate regions may delay planting and plant establishment as a result of mulch keeping soil cooler in the spring (Halde, 2012). Low soil temperature, one of the difficulties facing organic no-till, maybe significantly higher under grazed green manure plots. Higher soil temperatures in spring in grazed areas may facilitate earlier seeding of cash crops, which is an effective strategy for weed competition.

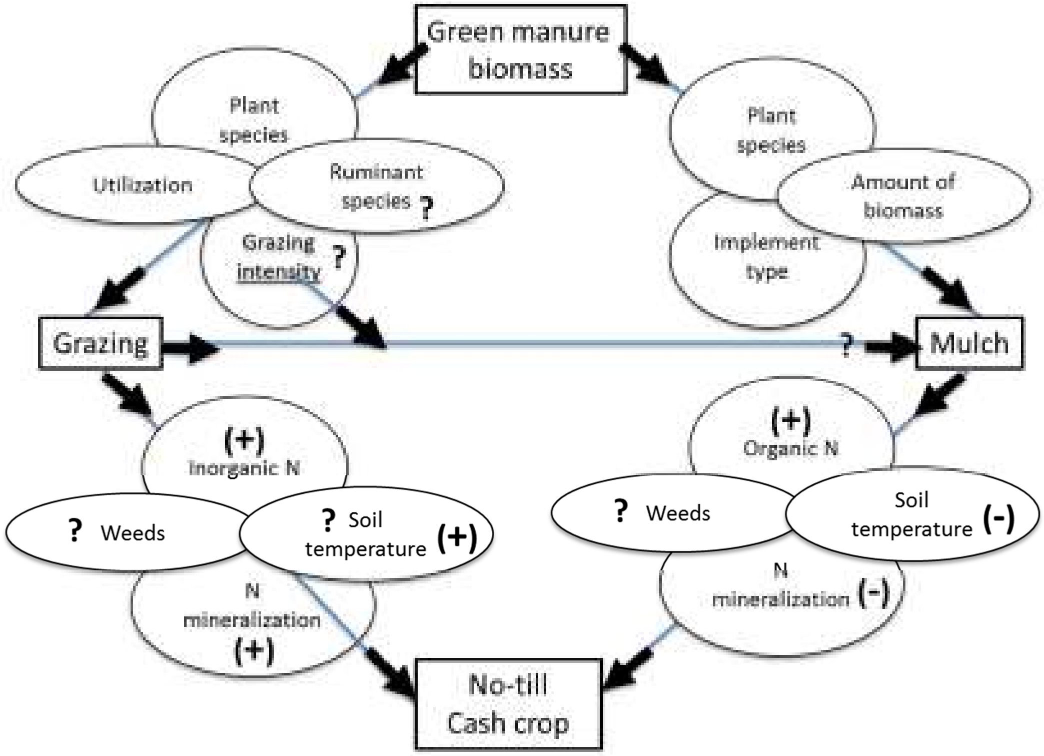

Figure 8.2. Processes and factors involved in achieving no-till organic cash crop production. Question mark (?) icons represent research needs and unknowns. Plus (+) and minus (-) icons represent increase and decrease in a given factor respectively.

Utilization of annual green manures by sheep has been rarely investigated in western Canada. Sheep readily consumed most of the green manures tested in this study. In the light of evidence that grazing maybe an effective tool to reduce tillage in organic systems, knowledge of utilization rates *ad libidum* emerges as a vital theme. For instance, to achieve successful establishment of no-till organic crops, a certain amount of mulch is needed as a ground cover. Grazing intensity and utilization management can have a direct impact on the success of organic no-till crops. Strategic grazing can leave a sufficient residue biomass on the soil surface to protect soil from wind and water erosion. This study is the first to report on utilization rates of annual organic green manures in western

Canada. More information is need on grazing intensity and utilization management to make sound management decisions for successful execution of organic no-till.

The present study focused mostly on the agronomic aspects of green manure systems. There is a need to investigate some of the fundamental processes in the plant, grazing and soil interface. Comparative rumen and soil decomposition studies involving different green manure species are one of the first that need to be investigated. Soil microbial responses to grazing under perennial systems have been investigated but there is very limited data on grazing of annual species. For instance, how does grazing annual green manure affect arbuscular mycorrhiza? What are the implications of higher soil microbial diversity found in grazed systems (Acosta-Martinez et al., 2010) for productivity in annual systems? How do annual grazing systems perform in terms of soil quality compared to perennial systems?

Weed control in reduced tillage systems through grazing has scarcely been discussed in the literature. Using grazing, weeds can be controlled during the green manure year, before cash crop seeding and after cash crop harvest (Figure 8.2). Grazing at various phases of the rotation not only provides weed control but also improves nutrient cycling. Since some of the weed species have similar nutritive value as common forage species, grazing weeds along with the crop residues can be captured in animal weight gains.

Extending the grazing season and designing new green manure systems

In the present study green manures were grazed only once, which may not be economical for most producers. High seasonality of forage production increases the cost of feeding animals during forage deficit periods such as winter and early spring. Winter hardy species can be used in Midwestern USA to provide feed in the early spring (McCormick et al., 2006). In western Canada such efforts are limited by the colder climate. Ideally green manures should provide forage for ruminants all through the growing season and into early winter. There is a need to establish whether autumn seeded winter annuals or perennials can provide forage in the early months of the spring. Summer annual crops can be seeded at different dates to ensure continuous forage supply throughout summer.

Plants with regrowth potential after grazing should also be explored. For instance instead of incorporating the second cut of berseem clover to soil (Shrestha et al., 1999), grazing can be used as a management tool to provide forage for animals and N for the following crops. The present study showed that some of the late season green manures could provide forage biomass in the autumn. Species with swath grazing potential should also be investigated (i.e. Tanaka et al., 2005). Stockpile grazing has been explored to a limited extend in western Canada, and may be more effective in terms of nutrient distribution than swath grazing. Evidently, there are a number of opportunities to improve green manure systems involving ruminants. Ultimately, economic considerations such as field operations and seed cost must be investigated to determine the feasibility of such systems.

More research is also needed to investigate the potential role of grazing to increase nutrient supply in diverse systems including perennials. Perennial forages, shrubs and trees can extract nutrients that are otherwise not available to the system. In other parts of the world such as in the semi-arid Mediterranean region (Ghassali et al., 2011) and in semi-tropical areas of Brazil (Landers, 2007) shrubs and trees are parts of crop-livestock systems. Ruminants can be effective tools to process and distribute these nutrients around annual crop production areas. Another area of interest in organic farming is whether grazing can be used to terminate perennial forages and weaken perennial weeds. It appears that, presence of ruminants in cropping systems creates new opportunities to potentially increase cropping systems performance.

Keeping the ground covered and microbes fed

Based on what is known about positive benefits of reduced tillage on soil ecology, the reduced tillage green manure systems investigated in the present study have potential to improve soil microbial and fungal function and diversity. For instance, in the grassland systems, defoliation of plants by herbivores leads to root exudation and subsequent increased activity of microbes in the rhizosphere (Bardgett, 2005). Microbial activity, in turn, enhances N availability and benefit plant growth. While these processes may have played a role in the present study, they require further investigation.

In extended grazing systems, where perennials or annual plants with re-growth potential (i.e. Italian rye grass) are grazed, total seasonal biomass productivity may be improved upon grazing. Such “non-nutritional” benefits (i.e. not related to urine and faeces N) provide an additional incentive to integrate crop-livestock production. The challenge, therefore, is to design strategic grazing systems where ground cover, animal performance and N benefit to cash crops are optimized.

Late season green manures may also be beneficial to soil fauna by providing ground cover when fields are normally left bare after the harvest of cereals. Reduced tillage late season green manures provide longer term soil cover than conventional tilled green manures. In the present study, reduced tillage late season green manure systems avoided tillage for 20 months from the seeding of fall rye in year 1 to harvest of wheat in year 2. For instance, in relay cropped red clover system this reduction in tillage was possible. There are a number of soil quality and health implications of keeping soils covered with plant material. Particularly in relay cropping systems perennial roots are active even when visible plant growth ceases (Lipson and Schmidt, 2004). Exudates from living roots may provide nutrients for microbial populations utilizing these resources. As discussed above, increased microbial activity improves the N availability and enhances soil heath (Paterson, 2003).

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